Improved Tank Testing Methods

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in cooperation with

Todd Pacific Shipyards Corporation

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FOREWORD

This is one of the many projects managed and cost shared by Todd Pacific Shipyards Corporation as part of the National Shipbuilding Research Program. The Program is a cooperative effort between the Maritime Administration's Office of Advanced Ship Development and the U.S. shipbuilding industry. The objective, described by the Ship Production Committee of the Society of Naval Architects and Marine Engineers, emphasizes productivity.

The investigation was assigned to the Division of Engineering Sciences, Southwest Research Institute, San Antonio, Texas, which has other extensive research experience in ships' tanks relating to loads, ventilation and explosion phenomena. Dr. R.L. Bass, III served as the Project Manager. The Principal Investigator was P.A. Cox. E.B. Bowles, J.C. Hokanson and R.L. Mason participated as project team members representing talents associated with structural analysis, experimental fluid mechanics, instrumentation technology, statistics and chemistry.

L.D. Chirillo was the R&D Program Manager who provided direction to the researchers and had overall cognizance in behalf of Todd Pacific Shipyards Corporation, Seattle Division.

Special appreciation is expressed to W.R. Clary, Chief Naval Architect, General Dynamics, Quincy Shipbuilding Division, for extraordinary guidance and assistance to the researchers.

Appreciation is also expressed for the constructive comments, guidance and assistance received from:

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National Steel & Shipbuilding Co.
Members, SNAME Panel SP-2

SUMMARY

The purpose of this project was to seek new methods for testing integral tanks in ships which would improve shipbuilders' productivity while not detracting from assurances for safety of shipbuilders' test personnel, regulators' inspectors, operators' crews and ships.

Investigations included:

- An extensive literature search to discover new methods for testing ship tanks
- A survey of tank testing as practiced in shipyards worldwide
- A survey of the rules of U.S. and foreign classification societies which govern tank testing
- The development of criteria for acceptance of new test methods
- Evaluations of:
  - — the hydrostatic test as a structural test
  - — the use of air in structural testing
  - — the use of statistics in tank testing
  - — new methods for improving visibility in leak detection
- A ranking of new test methods according to their potential for improving productivity in tank testing and laboratory evaluations of the most promising methods, including those now in use by shipbuilders.

Key findings and important conclusions which were reached as a result of these investigations are:

- Greater assurance of tank tightness is provided by a low pressure air and soap test than by a hydrostatic test
- A hydrostatic test does not subject the tank to its design loads, and very few structural defects are discovered by hydrostatic testing
- For any new test method, shipbuilders emphasize increased productivity, whereas regulators emphasize improved leak visibility
- There are many methods of leak detection. However, none improve productivity relative to the low pressure air and soap test and also provide equal or greater leak detection sensitivity
- Coatings and primers will effectively seal flaws (in a laboratory environment) which are much larger than the minimum flaw size detectable by current tightness testing methods
- Statistics a branch of mathematics, not now used in tank testing, can be applied for more scientific collection, analyses and interpretation of tank testing data. Sampling in accordance with principles of statistics offers the possibility of (1) removing shipbuilder and inspector bias in the selection of tanks to be tested, (2) reducing the amount of tightness testing in shipyards which consistently produce tight tanks and (3) providing known assurance levels for tank tightness.

Based on these findings and others reported in the Conclusions, three important recommendations are made which, if accepted by shipyards and regulators, can be implemented immediately. They are:

(1) Regulators and shipbuilders should accept the air and soap test, in place of the hydrostatic test, for all tank tightness testing.

(2) Regulators and shipbuilders should discard the hydrostatic test as a structural test for ship tanks.

(3) Inspectors and surveyors should adopt a record-keeping procedure for tank tightness testing from which an acceptance sampling plan for tank testing can be developed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

A. Purpose and Goals

This project was funded as part of the National Shipbuilding Research Program which is designed to improve productivity in shipbuilding. The purpose of this project was to take a fresh look at tank testing to see if improvements in productivity could be made in this particular area of ship construction. New methods for tank testing were sought which would:

- Be more productive in terms of time, manpower, materials and/or facilities.
- At least retain the same level of assurances that regulators and owners now have for both structural and liquid tight integrity and for safe implementation.
- Use the principles of statistics to establish sampling criteria.
- Permit scheduling flexibility, i.e., including testing even when waterborne and/or after coatings are applied.
- Not be inhibited by condensation.
- Cause little or no interference to other work in progress.

B. General Guidelines

This research program addresses itself exclusively to integral tanks on ships. Independent tanks, including all LNG tank primary boundaries, are excluded. Of principal interest are new test methods to improve productivity in tank testing. Weld quality, ship design and scheduling, either affect, or are affected by, tank testing and so are of secondary interest.

Both tightness testing and structural testing are covered in the study, but the major effort was directed toward improved tightness testing. For structural testing the question was asked "Can an air test be used in place of the hydrostatic test for structural testing or for demonstrating structural soundness of integral ship tanks?" Answers (opinions) to this question are presented in Section II.C and recommendations concerning structural testing are included in the Key Findings, Conclusions, and Recommendations.

An attempt has been made to use nomenclature which is most familiar to shipbuilders. Testing with air has been referred to as an air test instead of a pneumatic test but testing with water is called a hydrostatic test. A test, in which a soap solution is used to search for leaks on the boundaries of a tank pressurized with air, is referred to as

- an air and soap test
- a standard air test
- grooming

- an aggregate air test
- a tank pressurization test

The top two names are used most often. Grooming denotes the use of the air and soap test by the shipbuilder to check for tightness prior to inspection by the owner, surveyors, etc. "Air test" refers to any air-based test. Other test procedures such as air hose testing and vacuum box testing are so identified. In part of the report a distinction is made between tests by the shipbuilder to achieve tightness and tests conducted to obtain approval. For this distinction "grooming" and "approval testing" have been used.

Also, the terms regulators or regulatory agencies usually refer to agencies which regulate by law, such as the U.S. Coast Guard, as well as to classification societies. When a distinction is required, it is clear.

C. Approach

The work documented in this report was subdivided into three phases. These three phases were:

Phase I - Review, Evaluation and Planning

Phase II - Applied Research and Demonstration

Phase III - Documentation of Findings and Recommendations

This final technical report constitutes Phase III of the project. A task breakdown for Phases I and II and a brief description of how each task was performed follows.

Phase I

Task I.1 - Literature Search and Written Inquiries

Task I.2 - Visits to Shipbuilders, Regulators and Inland Tank Manufacturers

Task I.3 - Evaluation of Information

Task I.4 - Planning and Reporting

Phase II

Task II.1 - Laboratory Evaluations of the Hydrostatic and the Low Pressure Air and Soap Test

Task II.2 - Laboratory Evaluations of Selected "New" Leak Detection Methods

Task II.3 - Evaluations of the Leak Sealing Characteristics of Coating and Primers

Task I.1 - Literature Search and Written Inquiries

An extensive literature search was conducted using automated information retrieval services available through nationwide computer networks. Data bases accessed included:

NTIS - National Technical Information Service

COMPENDIX - Computerized Engineering Index

ISMEC - Mechanical Engineering Information Service

Oceanic Abstracts - Oceanic Abstracts and National Oceanic & Atmospheric Administration

World Aluminum Abstracts

Claims/Gem - U.S. Electrical and Mechanical Patents

NTIAC - Nondestructive Test Information Analysis Center

DDC - Defense Documentation Center

SHARPS - Data Base System Maintained by the Navy

In addition to the automated searches through these data bases, manual searches were made of MRIS (Maritime Research Information Service) and the Engineering Index.

Key words and algorithms used in the automated searches are given in the Appendix A. A total of 5038 "hits" were made. These are articles which satisfy the "key word" algorithms. Some were duplications because data base searches were repeated with different algorithms which may not have been totally exclusive and because articles are contained in more than one data base. Abstracts were scanned on each of these articles and those judged to be pertinent to the study were ordered. Approximately 100 articles were received and reviewed for content. The most important papers are cited as references to this report or included in the bibliography.

Written inquiries were sent to regulatory agencies (including classification societies) and shipbuilders world wide. Information was requested on the following aspects of tank testing:

Inquiries to Shipbuilders

- Narrative Description of Tank Testing Procedures
- Description of Problems Encountered
- Use of Statistical Methods in Tank Testing
- Records of Structural Failures (Structural Defects) Resulting from Proper Tank Tests (Air or Water)

- Cost Estimates for Tank Testing
    - Manhours
    - Materials
    - Time
- Suggestions for Improving Tank Testing Methods

Inquiries to Regulatory Agencies

- Current and Proposed Rules Regarding Tank Testing
- Explanation of Rationale Behind Current Tank Testing Regulations
    - Relationship between tests for tightness and structural integrity
    - Conditions where air testing is permitted
    - Inspection requirements for different joint types
    - Scheduling of tightness tests relative to special coatings
- Records of Structural Failures
- Problems of the Local Surveyor
- Definition of Acceptable Leak Rates
- Criteria for Acceptance of New Methods
- Statistical Methods Used in Tank Testing
- Suggestions for Improving Tank Testing

Replies were received from shipbuilders and regulatory agencies in the U.S.A., Canada and six foreign countries. Organizations which reponded to the inquiries are listed in Appendix B. Information from these replies, plus visits to domestic and foreign shipyards, formed the basis of the review of current testing methods (Section II), definition of the rules governing tank testing (Section III) and the setting of constraints on new test methods (Section IV).

Task I.2 - Visits to Shipyards, Regulators and Inland Tank Manufacturers

To gain firsthand knowledge of shipbuilding, particularly tank testing, visits were made to the regulatory agencies and shipbuilders listed below:

American Bureau of Shipping
U.S. Coast Guard
Avondale Shipyards Co.
General Dynamics/Quincy Shipbuilding Division

Ishikawajima - Harima Heavy Industries Co., LTD (U.S. office)
Newport News Shipbuilding Co.
Sun Shipbuilding and Dry Dock Co.
Davie Shipbuilding Ltd.

Cargo tanks, ballast tanks, double bottom tanks and fore peak tanks were examined in different stages of construction and on different ship types. Tank testing was discussed with shipyard managers, naval architects, tank testers, supervisors of hull construction, U.S.C.G. inspectors and ABS surveyors. Preparations for tank testing and some air testing was observed. Through these observations and discussions a better understanding of shipbuilding and of tank testing were obtained. These visits, more than anything else, contributed to an understanding of tank testing and to the definition of regulatory and practical constraints on new test methods discussed in Section IV.

Visits were also made to manufacturers of inland tanks to compare their testing procedures (primarily for large gravity tanks) with current practice in shipbuilding. Information gained from these visits is reported in Section II.B.

Task I.3 - Evaluation of Information

Articles from the literature were scanned and classified for further study as received. Information on potential test methods was organized for future evaluation. Forms were prepared and completed for each reply from the written inquiries. After preliminary evaluation, a team of "experts" in the fields of

chemistry
electronics
fluid mechanics
naval architecture (from the shipbuilding industry)
physics
statistics
structural mechanics

were called upon to aid in the evaluation of information received, in a ranking of potential test methods for their applicability to tank testing, in an evaluation of the use of the air test for structural testing, and to determine the prospects of extending the distance for visual detection of small leaks to 50 ft. Results of these evaluations are included in Section II.3.

Task I.4 - Planning and Reporting

Planning for Phase II was based upon the problem areas in tank testing which were discovered during the Phase I studies and upon the prospects for improving tank testing in shipbuilding by the introduction of new test procedures and test methods. All of the Phase I work was documented in an interim technical report, published January 1978, and all important parts of that report are included in this final technical report also.

Task II.1 - Laboratory Evaluation of the Hydrostatic and the Low Pressure Air and Soap Tests

Two types of laboratory evaluations were performed. First the flow rates of both air and water were measured through small capillary tubes of known size and with different pressure differentials across the length of the tubes. These tests were performed to give a quantitative number for leakage rates through small flaws of a size which is characteristic of weld flaws in a tank. A second series of experiments was performed to determine the minimum detectable flaw size with both the hydrostatic and the air and soap tests. These experiments were performed with the capillary tubes and also with weldments.

Task II.2 - Laboratory Evaluations of Selected "New" Leak Detection Methods

Laboratory tests were performed to evaluate three leak detection methods which seemed most promising for application to ship tank testing. These were:

- Dye Penetrant
- Ultrasonics
- Thermography

Tests were made to determine the maximum detectable flaw size and leak visibility for comparison with the results obtained for the hydrostatic test and for the air and soap test.

Task II.3 - Evaluation of the Leak Sealing Characteristics of Coatings and Primers

Several different coatings and primers were applied to test specimens which contained small orifices of known sizes and to weldments with known flaws. The ability of the paints to seal the flaws for pressures of up to 150 psig was determined for both brushed and sprayed test samples.

II. CURRENT TANK TESTING METHODS

The review of tank testing had three goals:

- Determine current practices in shipyards wordwide
- Determine the cost of testing integral ship tanks
- Compare tank testing methods used in shipbuilding with those used by builders of inland tanks

Information for the review was obtained by visits to domestic shipyards and inland tank builders and by written inquiries to shipbuilders and regulatory agencies worldwide. Results are presented in the following sections. Testing methods in use by shipbuilders are divided into those which are water based and those which are air based. Test methods rather than test procedures are discussed. Procedures for testing a typical ship may vary somewhat from shipyard to shipyard but, in general, follow requirements of the classification societies. About the only generalization which can be made is that small tanks which need special tightness, such as fuel oil tanks, aft peak tanks and double bottom tanks, are hydrostatically tested in drydock. All other tanks or boundaries are air tested in the drydock and selected tanks are hydrostatically tested after launch. Tanks selected for hydrostatic testing after launch usually include those adjacent to the cofferdams and pump room and some ballast tanks.

A. Ship Tanks

1. Water Based Tests

Three different types of water-based tests are currently used in tank testing by shipbuilders. These are:

- hydrostatic test
- hose test
- hydropneumatic test

The hydropneumatic test falls somewhere between a hydrostatic and an air test but has been included here because, along with the hose test, it is used primarily as a preliminary check of shell tightness.

a. Hydrostatic Test

For many years the hydrostatic test has been used by shipbuilders for checking tightness and strength of ship tanks; however, ships have increased in size until, now, few shipbuilders have facilities which will permit hydrostatic testing of the large cargo and ballast tanks with the ship on the blocks. Further, there is a danger of overstressing the bottom of the ship under the heavy liquid load. Hence, except for small tanks, most shipyards hydrostatically test the tanks after launch. This is done along side the dock or during sea trials.

A typical procedure for a hydrostatic test on the blocks or at the dock is as follows:

1) Erect staging and install lighting in adjacent tanks as required

2) Secure staging planks and remove lighting in tank to be tested

3) Clean the tank to be tested, if required

4) Install piping and fittings for filling to the prescribed liquid head

5) Start filling of the tank

6) Inspect for leaks on exterior boundaries as the tank is filled

   - Close visual inspection of penetrations (6" to 24")

   - General inspection of total boundary with a strong light

   - Repair weeps (localized moisture) as found

   - Drop water level for repair of major leaks (running or dripping water)

7) After filling and leak repair, submit tank for inspection by owner, inspector or surveyor

8) Repeat Step 6 as necessary

9) Pump out water

10) Clean tank and remove staging and lighting as required

In normal testing no additives are used to color the water or to reduce its viscosity; however, for testing of submarine hulls, the Navy requires that an additive be used to reduce viscosity.

A tank tested by the above procedure may or may not have been groomed with air. As a minimum, most tank testers will conduct a drop test with air to check for major leaks prior to the hydrostatic test. If the hydrostatic tests are to be conducted during sea trials, all or most tanks will have been tested with either air or water before the trials and these tests will have been approved by the inspectors and/or surveyors. During trials little or no staging is used and the close visual inspection of penetrations may not be obtained. Filling and draining is by the ship's pumps so that fill and drain times are reduced. Also, cleanup problems are often less with sea water than with water used at the shipyard. Even with these advantages, testing during sea trials can be costly if it is disruptive to other work in progress and extends the duration of the trials.

b. Hose Tests

The hose test is not used as a final test on tank boundaries. It may be used as a preliminary check of the ship's hull in certain areas prior to launch, but these same boundaries will be subsequently checked after launch by visual inspection below the water line or by observing the absence of water buildup in compartments. It has also been used for checking covers, such as the covers over LNG tanks and watertight doors.

There is no universal standard for the hose test. The Navy specifies a minimum pressure at the nozzle of 50 psi, a minimum nozzle diameter of 1/2 inch and that the nozzle be no further than 10 feet from the structure to be tested. Few shipbuilders gave requirements for hose testing. Those which did, specified nozzle pressures of about 30 psig and a nozzle diameter of 1/2 inch but set no minimum distance from the nozzle to the structure to be tested.

c. Hydropneumatic Test

This method was used for testing tanks in the transition period between hydrostatic and air testing of tanks with the ship on the blocks. Partial filling allowed loads on the blocks at acceptable levels and the use of air to pressurize the top of the tank gave bottom pressures intermediate to the hydrostatic and the air test. Survey results indicate that this test is seldom used today. Some yards occasionally use a few feet of water in the bottom of tanks to check the shell for leaks. Air pressure may or may not be applied. Some shipbuilders recommended that the hydropneumatic test, with the ship on the blocks or in the quay, be substituted for the full hydrostatic test.

2. Air-Based Tests

All tests which use air, gas or a mixture of air and gas as the fluid medium have been included in this section. Test methods are then classified by the means of detection, i.e., pressure drop, soap bubble, ultrasonics, tracer and chemical methods. A further breakdown is used for some detection methods. For example, soap is used as the means of leak detection for pressurized tanks, with the vacuum box, for local joint pressurization and in the air hose test. All of these methods are used at shipyards for tightness testing; however, chemical and tracer methods were only reported for tightness testing of LNG membrane tanks.

a. Pressure Drop

A pressure drop test is widely used by the Navy as a completion test for integral ship tanks. For tanks which must be oil tight or watertight the allowable pressure drop, over a period of 10 minutes, is zero, starting with a pressure of 2.0 psig. Of course, if leaks are present, they are usually located with a soap solution. The pressure drop test is commonly used by shipbuilders as a preliminary check for large leaks, before performing either an air and soap test or a hydrostatic test. For this application, no rigid guidelines are used. Large leaks, of the type sought by this pretest, are usually obvious.

b. <u>Soap Bubble</u>

(1) <u>Tank pressurization</u>

Applying a soap solution to the joints and seams of a pressurized tank is the most common test procedure used by shipyards for leak detection. It replaced the hydrostatic test for checking tightness of tanks prior to launch, as ships and tanks increased in size. This test can only be conducted after tank completion. A typical test sequence is as follows:

1) Erect staging and install lighting in adjacent tanks as required

2) Install hoses, gages and pressure relief equipment

3) Secure and pressurize tank with air to 2.0 psig - 3.5 psig

4) Observe tank pressure vs time to provide indication of large leak (rapid ΔP)

5) Soap all fillet welds, erection joints, penetration boundaries, etc. on exterior boundary (Soaping Procedure)

   - Soap applied with brush or spray
   - Additives are sometimes added to soap solution to extend inspection time
   - Seams inspected for bubbles immediately after soap application
   - Repair small leaks (a small cluster of bubbles after a few seconds) with air in tank
   - Repair large leaks (a fist-sized cluster of bubbles after a few seconds) by dropping air pressure prior to welding

6) Re-pressurize and inspect repaired areas as required

7) Submit tank for inspection by inspector and/or surveyor

8) Repeat soaping procedure as necessary (Step 5)

9) Relieve tank pressure

10) Remove staging and lighting in adjacent tanks as required

11) Clean soap solution from tank walls

Some shipyards, particularly foreign yards, cycle the pressure during tank pressurization. For example, the tank may be pressurized, initially, to 3.0 psig; the pressure is then lowered to 2.0 psig before the soap solution is applied. Other yards perform the entire test at 3.5 psig.

Many different methods are used to guard against accidental overpressurization. Some of the methods reported are:

- The tanks are pressurized with shop air (~90 psig) through a 1/2 inch diameter hose. A manometer is used to monitor air pressure. Tank pressure is controlled manually.

- Tanks are pressurized with shop air. Two gages, one dial gage and one column gage, are used to monitor tank pressure. A 1/2-inch relief valve with a setting of approximately 5 psig is placed on the tank.

- A large (approximately 8-inch diameter) water filled manometer is used to control air pressure. It is designed so that overflow begins at 2.0 psig and the tube is sized to equal the inlet flow (with a 2.0 psig pressure differential across the manometer).

- Tanks are pressurized with a compressor plant which has a limit pressure of 3.0 psig. Pressurization is through a 4-inch hose.

The last two methods appear to offer the most failsafe approach to avoid tank overpressurization.

No standard soap solution was discovered from the survey; however, many shipbuilders mentioned special solutions, some of which were developed in-house. Inspection liquids which were cited in the replies are:

- C. P. Check

- Tercetyl

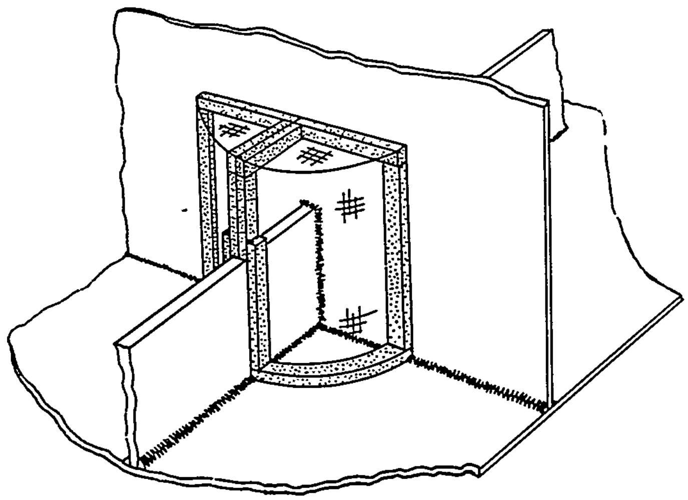
- Neofoamer

- Necal BX-Trocken

Major variations in this test from shipyard to shipyard are test pressures, inspection fluid and method of fluid application. The greatest single improvement in this test method would be to standardize and perhaps improve the indicating fluid.

(2) <u>Vacuum box</u>

Japanese shipbuilders have pioneered in the development and use of the vacuum box. As described here the vacuum box is a device used to achieve a pressure differential across a weld section to permit leak detection with a soap solution. [Some shipyards have checked for leaks with vacuum boxes by monitoring the vacuum in the box.] Typical boxes designed by IHI for testing fillet welds are shown in Figure II.1. They are being used for testing joints on erection units. The boxes have transparent windows so that the soaped weld can be observed, and edges in contact with the tank structure have flexible seals. A vacuum of about 7 psig is achieved by means of an air eductor. Box geometry is matched to the joint geometry so that butts, fillets, corner joints and some penetrations can be tightness tested. The same inspection fluid is used for vacuum box testing as for testing a pressurized tank.



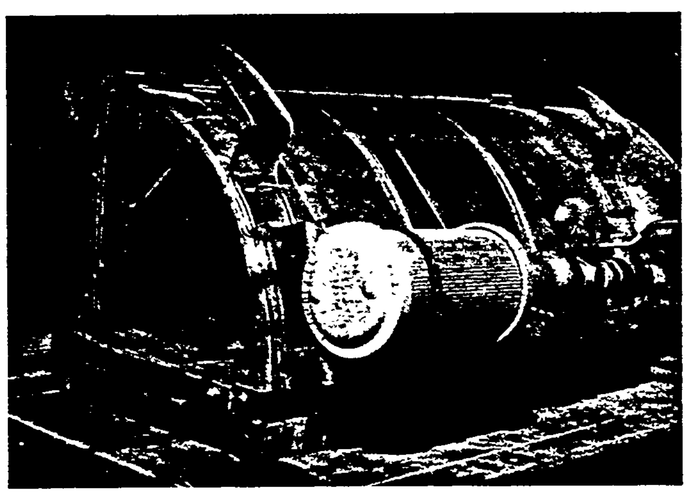


FIGURE II.1. VACUUM BOXES FOR TESTING FILLET WELDS. Each box features soft thick gaskets, a valve-eductor-silencer assembly and a fitting for connection to a compressed-air system. Some are made in two parts for testing flat-bar, tee or angle penetrations of tank boundaries before a block is erected. Others are hemispheres sized to inspect various deck fittings, e.g., for sounding tubes and even hatches of about 3-feet diameter.

The vacuum box offers the advantage of being able to test components of the tank for tightness very early in construction, i.e., at the shop or pre-fitting stage. At this stage of construction the welds are easily accessible for testing and repair. Testing at this stage also reduces the scaffolding required to obtain access after assembly. The most troublesome joints, the wraps and collars at the penetrations of longitudinals through transverse bulkheads, sometimes cannog be easily tested by this method. The complex geometry of these penetrations makes the design and sealing of boxes very difficult. Hence, some shipbuilders test collars and some T-joints by localized pressurization behind the weld.

(3) Local joint pressurization.

So that joints, such as double fillet welds at T-connections and fillet welds around collars and wraps at bulkhead penetrations, can be checked for leaks before tank completion, some shipbuilders have devised means of pressurizing these joints. Figure II.2 shows a typical arrangement for pressurizing the joint between a transverse bulkhead and the deck. Two or more plugs are installed so that testers can be certain there are no obstructions and that the full joint is being pressurized. Pressures used for testing are typically 30 psig or even higher. Because of the small areas exposed to the pressure, shipbuilders reason that there is little danger of overpressurization. A soap solution applied to both sides of the joint is used for detecting leaks. After testing the plugs are welded to seal the joint. This final weld may be checked in subsequent testing after tank completion.

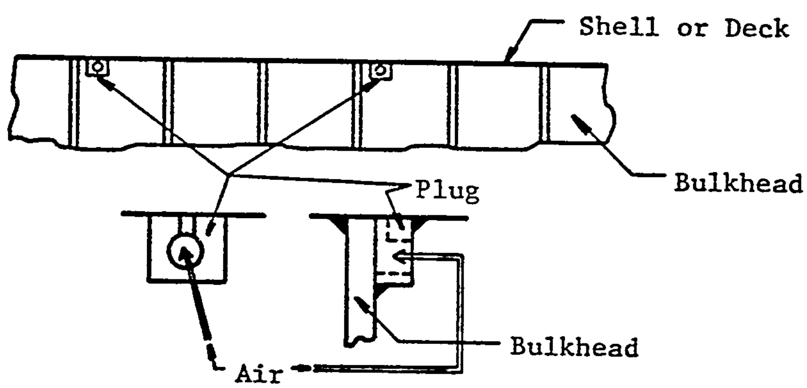


FIGURE II.2. PLUGS FOR PRESSURIZING A T-JOINT

A similar procedure is used for pressurizing collars except that no plug is required. A hole is drilled through the collar to give access to the space between the collar and the bulkhead. Some shipyards tap the hole; others may secure the air supply to the collar by external pressure. Both sides of the collar can be tested for tightness by this method. Higher pressures and a check of both sides of the joint with this method should guarantee a tighter joint than is achieved by tank pressurization.

(4) Air hose test

In the air hose test (also called a blow test) high pressure air is directed against one side of a joint and checks for leaks are made with a soap solution on the opposite side. For this test the Navy specifies a nozzle diameter of about 3/8 inch, nozzle pressure of about 90 psig and that the nozzle shall be held as close as possible to the structure. Shipbuilders which provided information on the air hose test give similar test requirements.

Navy specifications allow the air hose test for superstructure boundaries that cannot be air tested, testing tightness of structures separating two main machinery spaces and as a completion test for bulkheads separating cargo holds and a main machinery space, where the main deck cargo hatches are not designed to be airtight under a pressure head. Few shipbuilders mentioned the air hose test in their replies. Evidently, its use is very limited in normal tank testing.

c. Ultrasonics

Ultrasonic devices are used principally with air under pressure, as a means of locating the leak. These devices respond to sound above 30 KHz which is generated by the air escaping through a flaw in the structure. Operating principles are covered in Section V.D.2, A Survey of Leak Detection Methods. The method is discussed here, as well as under potential methods, because it has been used in tank testing, but only to a limited extent. Routine tank testing with ultrasonics, in place of air and soap, would be new to most shipbuilders.

Ultrasonics, for leak detection, has been most useful in shipyards for locating relatively large unusual leaks in tanks and for testing compartments in the superstructure. To locate unusual leaks which cannot be found by routine soaping of the boundaries, one shipyard places a tank tester with an ultrasonic probe inside a pressurized tank. An experienced user can find the leak very quickly (it might be a hole in a pipe which is hidden by a hanger).

An ultrasonic device is useful for testing compartments in the superstructure because these compartments are usually filled with equipment or access to their outer boundaries is restricted. Again, the tester looks for leaks from inside the pressurized compartment. For compartment testing very low pressure air is used.

One government shipyard, which performs maintenance and repair, uses ultrasonic devices extensively for leak detection and troubleshooting of operating equipment. In this shipyard the ultrasonic probe basically replaces the soap solution for leak detection in pressurized tanks, or with the air hose test. It is also used in conjunction with a sound generator. The sound generator, placed on the opposite side of the structure from the probe causes ultrasound to be emitted from small flaws in the structure. This approach is used most often in weld repair. Immediately after the weld is made, it is brushed and tested with the ultrasound generator and probe. Flaws found are immediately repaired and retested.

With the exception of personnel at this government shipyard, tank testers, in general, do not believe that ultrasonic methods are sensitive enough (in the shipyard environment) to assure a tight tank. However, this method has many potential advantages over the air and soap test. As a result, an in depth analysis of this method has been performed during the Phase II work.

d. Other Methods

Other methods being used by shipbuilders for tank testing fall into the categories of chemical activiation and halogen tracer, which are discussed in Section V. Both of these methods are being used for tightness testing of LNG membrane tanks and so are regarded as "new" methods for testing integral tanks.

As described in Section V.B.2, chemical activation is based on a color change induced in a solution (the developer) by reaction with a trace gas. The developer is applied to the tank boundary, in the same manner as the soap solution; trace gas is diffused in the air inside the tank (under pressure) and escapes through flaws in the structure. Reaction with the developer at the leaks produces a visible discoloration for leak detection. For the test method reported, the inner barrier space in a membrane tank is charged at very low pressure with ammonia (the trace gas) and nitrogen. A developer solution (which produces a green stain) is applied to seam welds on the inner barrier for leak detection and location.

The use of a halogen gas, in this instance, Freon, has also been used for checking seam welds in membrane tanks. In this method the inner barrier space is charged with Freon under a slight positive pressure. Leaks are detected with "sniffers" similar to those used in the air conditioning industry.

B. Inland Tanks

Many tanks manufactured for inland service are required to be liquid tight. Gravity tanks, those intended for use below 15 psi, are tested according to the provisions of American Petroleum Industry Standard 650. Liquid natural gas tanks are tested according to API Standard 620, and pressure vessels are tested according to ASME codes. Since the gravity tanks resemble typical ship tanks most closely, tank testing for these types of tanks are of principal interest to this study.

Oil storage tanks are typical inland gravity tanks. Many of these tanks are about 300 ft in diameter and about 60 ft tall. Seams in the bottom of the tank are tested using the vacuum box and soap. One manufacturer stated that a minimum of 3 psig vacuum is used. Often these tests take place before the side shell is completed. The joint between the tank bottom and side shell is required by API 650 to be tested with a six inch head of water. However, as a pretest manufacturers indicated that diesel oil or other penetrants are applied to the joint on the inside and the outside is examined for evidence of leaks. After completion, the side shell is usually air tested with 2 psig air pressure. Leaks are located with soap solutions applied to the outside weld seams. The above tests are considered preliminary. The final test is either a hydrostatic or a hydro-pneumatic test. In the hydrostatic test, the tank is filled with water for a period of time specified by the tank purchaser, from one hour to several days. In the hydro-pneumatic test, the tank is filled to its design capacity with water, vents are closed and the tank is pressurized to half the design pressure. Then the pressure is gradually increased to 1.25 times the design pressure and held for one hour. Finally, the pressure is released slowly. During the final tests, the tank is inspected for leaks and also signs of "distress" in the shell. All detected leaks are repaired.

Manufacturers of pressure vessels were surveyed to determine if their tank testing techniques are any different than those used for gravity tanks. We found that virtually all their leakage tests are performed with water or high pressure air. On occasion halogen or helium leak tests are performed using 10 to 100% tracers. The personnel contacted felt that in a typical plant environment, tracer tests are not effective in locating leaks. Whenever possible, tanks required to be tested with tracer methods are pre-tested with air or water to assure the manufacturer that the vessel is tight.

From our discussions with inland tank manufacturers, it became apparent that they have little incentive to improve their tank testing methods. First, tank testing does not severely interfere with other activities at the construction site. There are no support problems and water can be left standing in a tank for several days to prolong a test if desired. Usually there are few penetrations into the tank, so the number of leak prone assemblies is reduced. Finally, the codes currently specify the type and extent of leak testing required. Since the manufacturers feel that the cost of testing is not significant there is no reason for them to invest in new technology for tank testing.

C. Evaluations of Current Methods

1. Opinion Survey

Shipbuilders and regulatory agencies were asked to identify problems with current testing methods and give suggestions for improvements. Problems were cited for both air-based and water-based methods, and appeared to apply principally to the standard air test or to the hydrostatic test. Thus, problems were summarized for these two tests and are given in Tables II.1 and II.2.

Every problem reported by any shipbuilder is included in the list. The number of shipbuilders citing a particular problem is also given. For each test, problems were divided into two groups. One group contains problems which affect, primarily, inspection and one group contains problems related to construction. When a problem was cited by regulatory agencies, it is preceded by a "+" sign. Thus, 3 + 2 for the first entry in Table II.1 indicates that three shipbuilders reported the problem and two regulatory agencies.

As expected, most of the problems with air testing pertain to inspection and most of the problems with hydrostatic testing pertain to construction. Also, replies from regulators cite problems only for air testing. It is clear from these replies that, in general, shipbuilders prefer air testing

TABLE II.1. PROBLEMS WITH AIR TESTING

Problem Identified	No. of Times* Cited
Inspection	
Requires close examination of welds	3 + 2
Limited observation time	2
Reliability of test depends on inspection fluid	1
Not representative of service conditions	2 + 1
Leak indication provided only where indication fluid is applied	1
Welds are often not conveniently accessible	2
Danger of overpressurization (safety)	5 + 1
Carrying inspection materials around tank is dangerous	1 + 1
Test pressure is low, limited by tank top	1
Construction	
Safety relief valves must be installed	1
Temporary access openings must be blanked off	1
Cost of staging	3
Time consuming	3
Doesn't give indication of structural strength	2
	28 + 5

*Definition of N + M
N = Shipbuilders
M = Regulatory agencies

TABLE II.2. PROBLEMS WITH HYDROSTATIC TESTING

Problem Identified	No. of Times Cited
<u>Inspection</u>	
Adversely affected by condensation	4
Welds are often not conveniently accessible	2
Leaks may be plugged by floating debris	1
<u>Construction</u>	
Residual moisture affects coating adhesion and accelerates corrosion	2
Salt water accelerates corrosion	1
Water is expensive and not always available	3
Adversely affects draft and trim	3
Adversely affects construction progress	3
Long fill and drain times	6
Extensive cleanup required	3
Usually requires testing at sea	3
Water may freeze	3
Repair is time consuming	1
Outfitting berths often requires dredging to permit hydro testing	1
Planking must be secured	1
Electrical equipment must be removed	1
	38

over hydrostatic testing because it interferes less with construction. From the inspectors' and surveyors' point of view, a distinct advantage of water is that there are fewer problems which interfere with inspection. Overall slightly fewer problems were cited for air than for hydrostatic testing.

Even though problems are encountered with air and hydrostatic test methods, each also has its advantages. For completeness, a list of advantages was compiled for each method and is given as Table II.3. Advantages were compiled primarily from visits to shipyards and conversations with tank testers, surveyors and inspectors. No breakdown in inspection or construction categories was made nor was the number of times cited recorded; however, as for the problems cited, advantages for air tend to favor construction and those for water favor inspection.

In general, new test methods should minimize the problems in construction as does the air test, minimize the problems in inspection as does the hydrostatic test and combine the best advantages of each. Shipbuilders, regulators and classification societies were asked for their suggestions for improving tank testing methods. Their replies are included in Table II.4. Suggestions apply not only to the testing methods but also to ship design and to the regulations and rules for shipbuilding. Suggestions were grouped into these three categories.

TABLE II.3. ADVANTAGES OF CURRENT TEST METHODS

AIR	WATER
• Quick Access for Leak Repair	• Long History of Successful Use
• Minimum Clean-Up After Testing	• Provides Representative Loads and Load Distributions on Tank Structure
• Air is Readily Available and Inexpensive	• Provides Leak Check of Total Tank Surface (not just soaped seams)
• Does not Affect Ship's Trim	• Leaks are Easy to Spot
• Less Disruptive of Other Work in Progress	• Testing Permitted After Coatings
• Allows Testing Before Launch	• Provides a Way to Test Open Top Spaces Such as Chain Lockers
• Leaks Inferred from Pressure Measurement	
• More Versatile: - Soap Test - Pressure Drop Test - Vacuum Box Test	

Of the suggestions, eight pertain to the regulations, five to testing and four to design and construction. To summarize, shipbuilders are asking for:

Testing
1) Improvements in leak detection
2) Ease in testing at the subassembly stage
3) Permission to test after coating

Design and Construction
1) Better design and construction to minimize leaks

Rules and Regulations
1) Elimination or reduction of hydrostatic testing
2) Setting of permissible leakage rates for tank boundaries
3) Acceptance of pressure drop test for tank approval

This project addressed itself principally to the improvements suggested under testing. It will also affect item 1 under Rules and Regulations because a test method is sought which will be acceptable to owners and regulatory agencies in lieu of the hydrostatic test for tightness testing.

2. Structural Testing

In addressing the subject of structural testing of integral ship tanks, the following aspects of the problem were considered:

TABLE II.4. SUGGESTIONS FOR IMPROVING TANK TESTING

Testing:	No. Times Suggested
Develop method which leaves permanent indication of leak	2
Improve indicating fluid for air tests	3
Add pigment to the air so that leaks are visible without soap solution	1
Perform more testing at subassembly stage	3
Establish permissible tank coating thickness as a function of air pressure	1
Design and Construction:	
Reduce length of joints tested, i.e., design ships so that more machine welds are made and less hand welding is required	1
Design tanks to withstand higher air pressures for better test credibility	1
Develop structural details and weld procedures to minimize leaks	2
Use "best" welders on structures prone to leakage or subject to testing	3
Rules and Regulations:	
Use air testing because it requires shortest time, interferes with construction progress only slightly, and leaves tanks dry for immediate coating	1
Waive hydrostatic test on "proven" tank design	3
Use hydro-pneumatic tests in dock in lieu of hydrostatic tests during trials	1
Bulkheads between tanks carrying the same cargo should have unique tank testing requirements, and testing should take place after application of coating	2
Because of the advanced state of structural analysis, eliminate hydrostatic tests, use air tests to demonstrate tightness, and computer analysis to demonstrate structural strength	1
Establish permissible leakage rate, similar to sliding watertight doors and valves	1
Use limited pressure drop as acceptance criteria	1
Use statistics to select tanks to be tested	1

- The purpose of structural testing

- Air versus water for structural testing

- The contribution of deflection measurements to a demonstration of tank structural integrity

a. Purpose

The purpose of tank structural testing should be to either (1) show that a tank will withstand its design loads (structural assurance) or (2) to contribute to quality control in building of ship tanks. It is clear that hydrostatic testing of a ship in dock or even during sea trials does not satisfy item (1). A ship is designed to operate in the "worst-case seas" that it is expected to experience over its lifetime. These sea conditions superimpose dynamic vertical, lateral and longitudinal acceleration on the static liquid head and induce "primary" stresses on the hull girder which can add to the "secondary" stresses associated with loads produced by tank contents. Further, the tank structure must be designed to withstand loads associated with liquid sloshing, which can occur in a partially filled tank, and to withstand repetitive loading.

Not only are the hydrostatic loads less than the design loads, but allowable stresses in the structure at the design loads are generally lower than yield, ultimate or critical buckling stresses and thus the structure should not permanently deform, buckle or fail even if the maximum design loads were imposed. Hence, a hydrostatic test at the design head cannot be regarded as a realistic verification of the tank's ability to withstand the design loading.

One goal of the inquiries to both shipbuilders and classification societies was to obtain data which would show the contribution of tank testing to quality control in tank construction. The inquiry asked for a record of structural failures or structural defects that have been detected with air and water tests. Cases of improper testing such as overpressurization were to be omitted. Only four shipyards out of 18 responding reported failures and the types of failures cited are listed in Table II.5. Failure as used here certainly does not denote a catastrophic type of rupture in the tanks but only sufficient structural deformation to prevent the tank from passing the hydrostatic "structural" test. In fact, most of the failures cited appear to be relatively minor.

TABLE II.5. TYPES OF FAILURES REPORTED

- Relative movement between ship's side and longitudinal bulkhead
- Buckling of web panels
- Girder face bars not adequately stiffened
- Distorsion of panel on primary barrier
- Buckling of free edge of bracket
- Minor structural defect in upper member of wing tank

A summary of tank failures reported by the shipbuilders is given in Table II.6. All results are for hydrostatic tests, which were properly conducted according to classification society rules. Note that only foreign shipyards cited failures and gave a sample size so that failure rates could be calculated. U.S. shipbuilders reported no failures and usually gave a time period, such as 20 years or 30 years, over which the observation applied. No attempt was made to estimate the number of tanks hydrostatically tested over such time periods, so the data was not included in Table II.6.

TABLE II.6. SUMMARY OF TANK FAILURES PRODUCED BY HYDROSTATIC TESTING

	U. S.	Foreign	Total
Total replys	4	14	18
Shipyards Reporting Failures	0	4	4
Shipyards Reporting Sample Size	0	6	6
For Shipyards reporting* Failures:			
Number of failures reported	-	22	22
Number of tanks hydrostatically tested**	-	2866	2866
Failures as % of tanks tested	-	0.77	0.77
For Shipyards Reporting Sample Size			
Number of failures reported	-	22	22
No. of tanks hydrostatically tested	-	6028	6028
Failures as % of tanks tested	-	0.36	0.36

*Only three shipyards reporting failures gave number of failures and sample size.

**When ships tested rather than tanks tested were reported, it was assumed that 18 tanks per ship were hydrostatically tested.

Of the 22 failures reported, 20 were from a single shipbuilder. Further, the failures cited were not so severe as to require retesting of the tanks after they were strengthened. Two shipbuilders, each reporting a single failure, indicated that a successful second test was performed after structural modifications were made. One shipbuilder reported that failures had occurred before finite element analyses became routine. Neither the number of tanks tested nor the number of failures were given, but the shipbuilder reported successful retesting after strengthening. Without extensive follow-up on the replies, it is not possible to determine whether or not all shipbuilders interpreted failures in the same way. Detailed guidelines of what constituted a failure were not given and so each shipbuilder interpreted failure in terms of his own past experience.

If we assume that all shipbuilders would have reported as a structural failure any deformation of the tank structure which was sufficient to warrant strengthening, whether or not retesting was required, then we have:

- o 3 shipbuilders reporting 22 failures out of 2866* tanks which were hydrostatically tested. Failure rate = 0.77% (22 ÷ 2866 x 100%)
- o 1 shipbuilder reporting failures but no specific data.
- o 3 shipbuilders reported no failures out of 3162* tanks which were hydrostatically tested.
- o 11 shipbuilders reported no failure but did not specify the number of tanks tested.

To compute a failure rate for all shipbuilders the following assumptions are required:

1) Failure rate for the one shipbuilder who reported failures but did not give data is the same as for the three shipbuilders who provided data, i.e., 0.77%.

2) Testing rate for the 12 shipbuilders who provided no data is the same as for the 6 shipbuilders who reported the number of tanks tested. Testing rate = (2866 + 3162) ÷ 6 = 1005 tanks hydrostatically tested per shipbuilder.

Based upon these assumptions, the total number of failures and tanks tested would be:

Tanks tested = 1005 x 18 = 18090

Failures = 0.0077 x 1005 x 4 = 31

This gives an overall failure rate of 0.17% (31 ÷ 18090 x 100%).

Another possible interpretation of the data is to consider only those failures which were severe enough to require retesting. Two shipbuilders reported one failure each and indicated that retesting was required. One shipbuilder reported that failures occurred which required retesting but did not give specific data. Here again, the failure rate per shipbuilder must be based on those reporting data. For these assumptions 3 failures occurred (which required retesting) out of all ships tested and the failure rate is 0.017% (3 ÷ 18090 x 100%).

Consider the higher failure rate of 0.17%. At this rate, for every 584 tanks which are hydrostatically tested, one tank is found to be defective and is repaired before the ship is delivered to the owner. If we assume that the 584 tanks are tested only for the purpose of detecting

* When ships tested rather than tanks tested were given, it was assumed that 18 tanks per ship were hydrostatically tested.

the one defective tank then the cost to the shipowners, shipbuilders and the classification societies of detecting the one defective tank is great; however, in current practice the hydrostatic test is regarded as both a tightness test and a structural test. The hydrostatic test is still used for tightness testing because of a lack of confidence in the air and soap test for demonstrating tightness.

As previously mentioned, most shipbuilders test all but a few small tanks (which are tested with water) with air before or after launch. After launch, several tanks are chosen on the basis of critical boundaries or by tank type for additional testing with water. If these hydrostatic tests are for tightness only, then they could be omitted if sufficient confidence can be established in the air and soap test or in another air-based test. If they are for strength alone, then a cost-benefit analysis is needed to show whether or not these structural tests are productive to the shipbuilding process. One goal of this research is to develop an air-based test that is acceptable to shipbuilders, shipowners and regulatory agencies in lieu of the hydrostatic test for tightness testing. If this can be done, then a cost-benefit analysis should be performed to provide a basis for evaluating the worth of structural testing in shipbuilding.

b. Air Versus Water

To compare the air test and the hydrostatic test for structural testing, the question was asked: "Does either test subject the tank or any part of the tank to its principal design loads?" As already discussed in Section II.C.2.a the hydrostatic test does subject the tank to the true static liquid load, but all dynamic loads such as liquid acceleration and wave bending are omitted; however, near the tank top the static liquid load may be the principal design load for a few components. For example it could set local plating thicknesses and local stiffener dimensions in parts of the tank top or near the top transverse bulkheads. This may occur because the dynamic liquid load is computed for the maximum cargo filling level and does not include a liquid load above the tank top as does the static liquid load. At lower levels in the tank the dynamic liquid load (or other loads) will most certainly govern tank scantlings.

Thus, the hydrostatic test may subject some components near the top of the tank to their principal design load; however, in this same region pressures produced by the hydrostatic test and the air test are approximately equal. This occurs because the maximum pressure in the air test is set by the static liquid load at the tank top.

In summary, both the air test and the hydrostatic test may subject some local components near the tank top to their principal design load. At other places in the tank and for the vast majority of tank structures, neither the air test nor the hydrostatic test provide a true test for structural strength. Because of this neither test is acceptable for structural testing and both are equally unacceptable for structural testing.

c. Contribution to Deflection Measurements

Deflections between tank longitudinal and transverse bulkheads are measured by some shipyards during hydrostatic testing on the first ship of a class. This is not a requirement of the regulatory agencies but may be required by the owner or performed voluntarily by the shipyard. One case of excessive deflection between tank bulkheads (or between bulkheads and the ship's sides) was reported as a failure by shipbuilders (see Table II.5).

In the summary of rules governing tank testing reported in Section III, no criteria were discovered for relating tank deflections to structural strength. If a deflection criteria is used, it must be related to a fairness criteria for tank walls or the ship's sides. Such a criteria may impose restraints on the structure which are well above those required for structural strength alone.

To be meaningful as a test of strength, deflection predictions at prescribed points in the structure and at prescribed loads should be made analytically for comparison with deflection measurement during tests. If this approach is taken, then it would not matter* whether the load is the hydrostatic pressure or 2.0 psig air. So long as measurements match predictions, confidence in the structure and in the analytical method used in the design and analysis is obtained. Further, analytical predictions could be made for both 2.0 psig air and for a liquid head. The calculated ratio of deflections could then be used to predict deflections with a liquid head from deflections measured with 2.0 psig air. To extrapolate measured deflections in this way requires that the ratio of deflections for the two loads be determined analytically. This is required because the distribution as well as the magnitude of the loading is different. If measured and calculated deflections for a 2.0 psig air test agree well, then confidence in the prediction of deflection for a liquid head is obtained.

d. Summary

From the data gathered from shipbuilders and from the arguments presented, the conclusions concerning structural testing are:

- A hydrostatic test does not prove tank structural integrity for the actual design loads.
- The failure rate of tanks subjected to hydrostatic tests is extremely low.
- Deflections in tank structures, measured during low pressure air tests, can be extrapolated, analytically, to predict deflections which are expected during hydrostatic tests.

*Conceptually, it would not matter whether the deflections were measured for 2.0 psig air or for hydrostatic pressure. From a practical standpoint, deflections in the air test will be much smaller than deflections in the hydrostatic test and this will affect the accuracy with which the deflections must be measured.

- o Deflection measurements are not sufficient to demonstrate tank structural adequacy (there are no acceptance criteria for tank structures based upon deflection measurements).

- o Deflection measurements can give confidence in analytical methods, when measurements are compared to analytical predictions.

3. Laboratory Tests

Laboratory tests were performed to measure flow rates of air and water through small flaws and to determine the minimum flaw size that could be detected with a hydrostatic test and with an air (and soap) test. These tests permitted a direct comparison of the two most common leak detection methods used to establish tightness in ship tanks and provided a basis for evaluation of other candidate leak detection methods.

To evaluate the use of air, water and other methods for leak detection it was necessary to develop a test procedure that would evaluate each detection method on an equal basis. To achieve this, stainless steel capillary tubes were used to simulate flaws typical of those detected during a tank tightness test. Round capillaries as small as 0.0061 inch in diameter were tested. Holes with smaller cross-sectional areas were achieved by flattening 0.0061 inch diameter round tubes in a vise. Using this technique it was possible to obtain a hole cross-sectional area as small as an equivalent 0.0016 inch diameter hole. For test purposes, all tubes were 0.375 inch in length (a typical ship tank plating dimension).

a. Flow Rate Calibrations of Test Capillaries

Flow rate calibrations for the round capillary tubes were obtained for both air and water. The purpose of these calibrations was to establish the flow rate of air or water passing through a given size hole. In addition, these tests assisted in determining the minimum detectable hole sizes for the detection methods that were being examined.

The flow calibrations for the round capillary tubes are pictured in Figures II.3 and II.4. Details of the calibration procedure are included in Appendix D. It should be noted that two water temperatures (40° and 80°F) were used for the water tests. This was to examine the effect of viscosity on the flow rate of water through a capillary. The calibrations indicated that the viscous effect on flow rate was insignificantly small over the temperature range tested. It should be noted that measurable air and water flow rates, though small, were obtained for the smallest hole tested (0.0061 inch diameter) even for very low pressure drops across the length of the tube. Since measurable flow rates were obtained for all of the test cases, additional tests were required to establish the minimum detectable hole size using (1) water and (2) a standard air test (with a soap solution). The results of these tests were used as a guideline for evaluating the alternative detection methods.

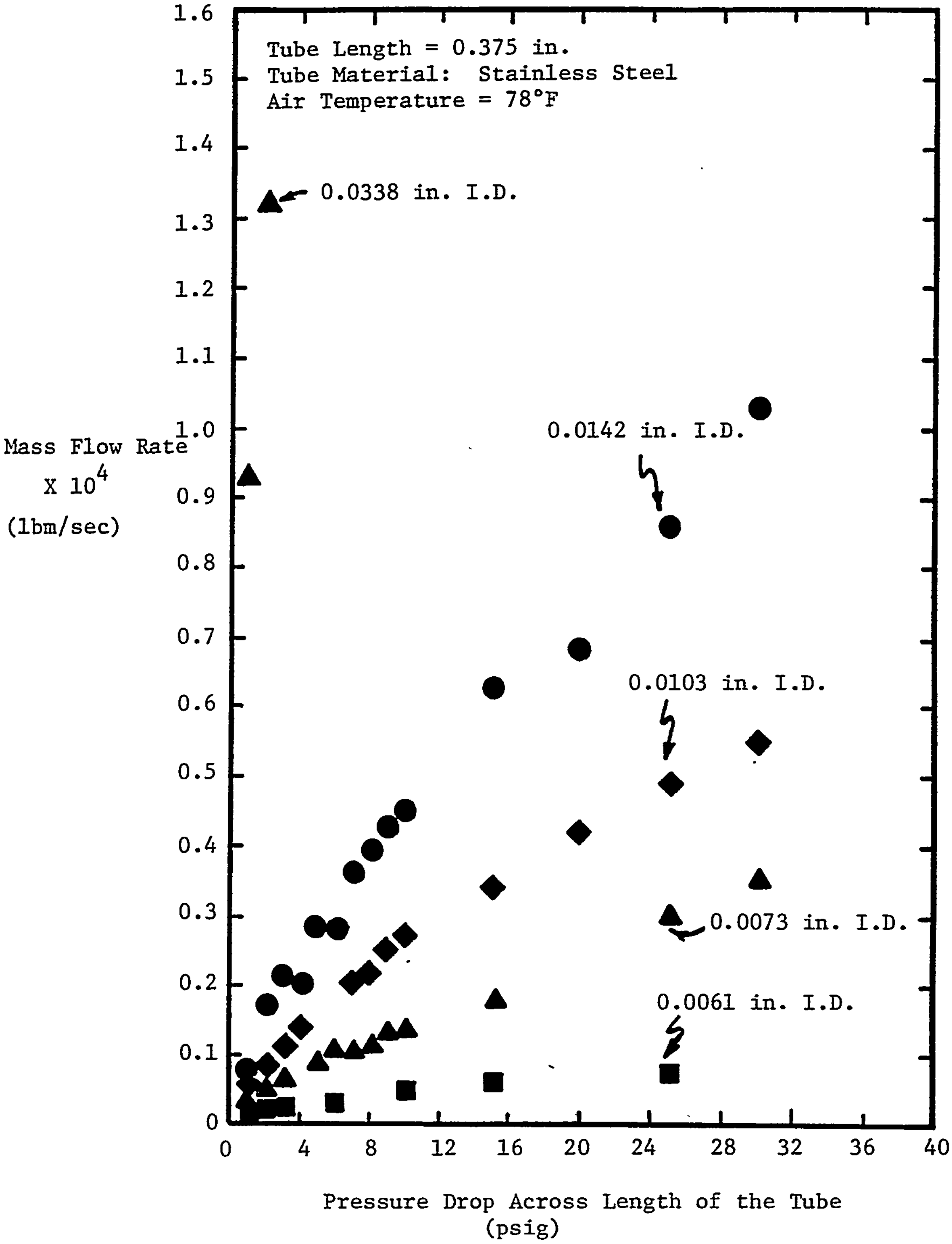


FIGURE II.3. AIR MASS FLOW RATE AS A FUNCTION OF PRESSURE DROP ACROSS THE LENGTH OF A CAPILLARY TUBE FOR VARIOUS DIAMETER TUBES

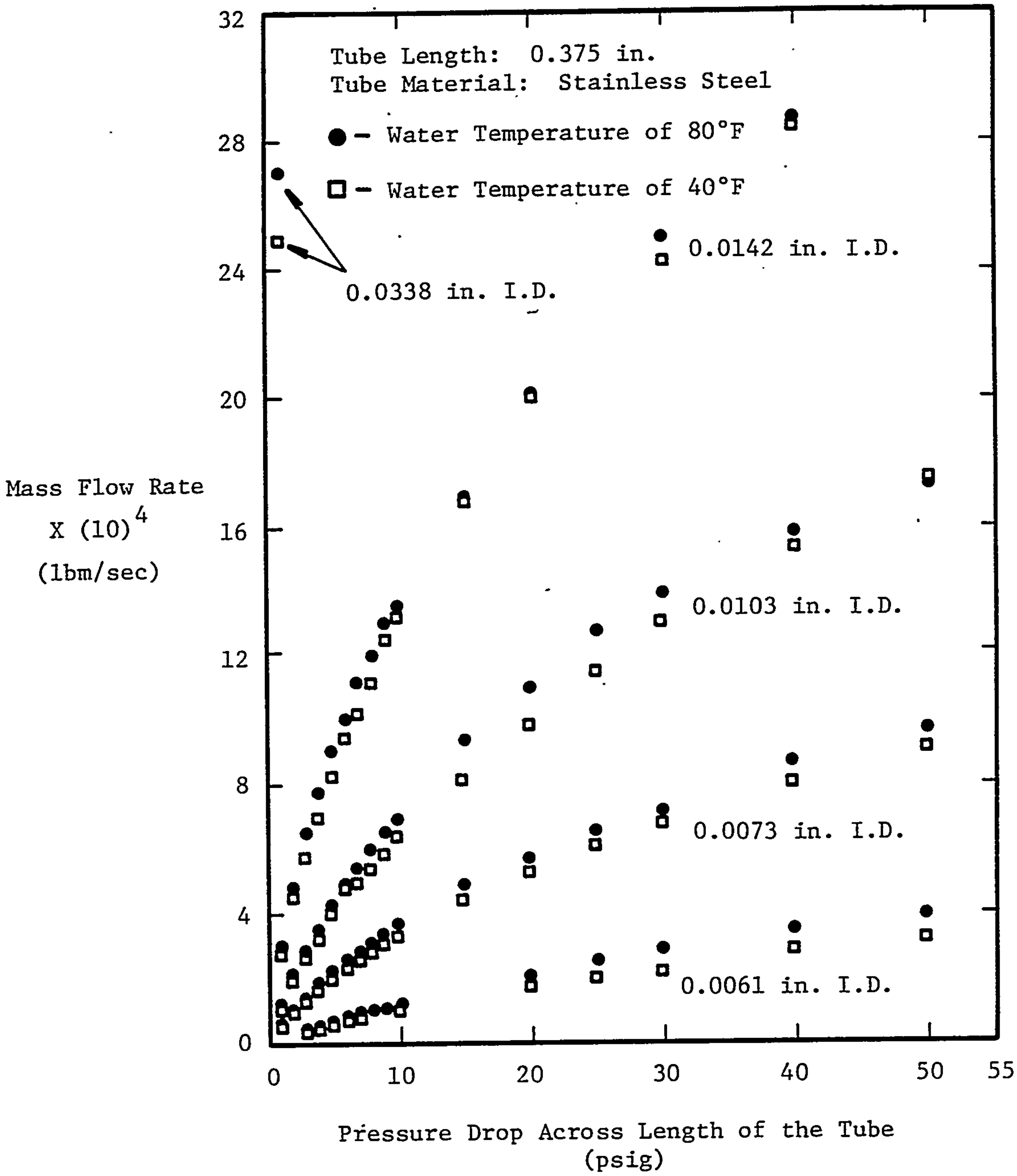


FIGURE II.4

WATER MASS FLOW RATE AS A FUNCTION OF PRESSURE DROP ACROSS THE LENGTH OF A CAPILLARY TUBE FOR VARIOUS DIAMETER TUBES AND VARIOUS WATER TEMPERATURES

b. Minimum Detectable Hole Size

The air-based test for a minimum detectable hole size evaluated four different soap solutions. These were (1) Snoop, (2) Leak Tec, (3) Magic-Wand, and (4) Tercetyl. Snoop, Leak Tec, and Magic-Wand are all commercially available products used for leak detection. Tercetyl is formulated by the Swedish Technical Control Institute for Moss Rosenberg specifically for use in leak testing of ship tank. Similar test results were obtained for each of the four soap solutions.

The minimum-detectable-hole-size test results for both water and air (with soap) are summarized in Table II.7. A water leak was considered detectable if a visible droplet formed on the outlet end of the test capillary. An air leak was considered detectable if visible bubbles formed in the soap solution at the outlet end of the capillary.

The lab tests only approximated actual tank testing conditions, but much insight was gained by evaluation of the test results. Table II.7 shows that a hole detected with water at the 50 psig pressure level was also detected with air and soap at about the 10 psig pressure level. However, the water droplet formed in this case was so small (less than one hundredth of an inch in diameter) that it was visible to the naked eye only at distances of less than one foot. In a large ship tank, a hole this size could easily be overlooked by an inspector. Contrastingly, the same hole was detectable at a distance of several feet when air (at the 10 psig level) and soap were used because a foamy area of bubbles formed at the leak. In a more practical test case, a water leak (at the 50 psig pressure level) that was detectable at a distance of five feet was also detectable with air and soap (at the 2 psig pressure level) at the same five-foot distance. The hole size at this detection level was on the order of 0.001 to 0.003 inch in diameter. Based on the test information, it is believed that the minimum detectable hole size in an actual tank tightness test using either water or air with a soap solution is in this range of 0.001 to 0.003 inch in diameter.

Results from Table II.7 are plotted in Figures II.5 and II.6 to show how the pressure drop affects the comparative accuracy of the air and soap test versus the water test. It is evident from Figure II.5 that an air test with a 2 psig pressure drop can detect a flaw that would be detected by a hydrostatic test in a ship tank that is 55 ft or less in depth. Also, a leak in the upper part of the tank is more likely to be detected by the air and soap test than by the hydrostatic test. For tank depths greater than 55 feet, a hydrostatic test can potentially detect smaller holes than can a 2 psig air test. However, the difference in accuracy of the two methods in this range of hole size is small. As a result, an air test at a 2 psig level is more likely to uncover leaks over the entire surface area of any size tank than is a hydro test. This conclusion assumes that loads and load gradients created by a hydrostatic test will not affect flaw size relative to air loads.

c. Tests on Weldments

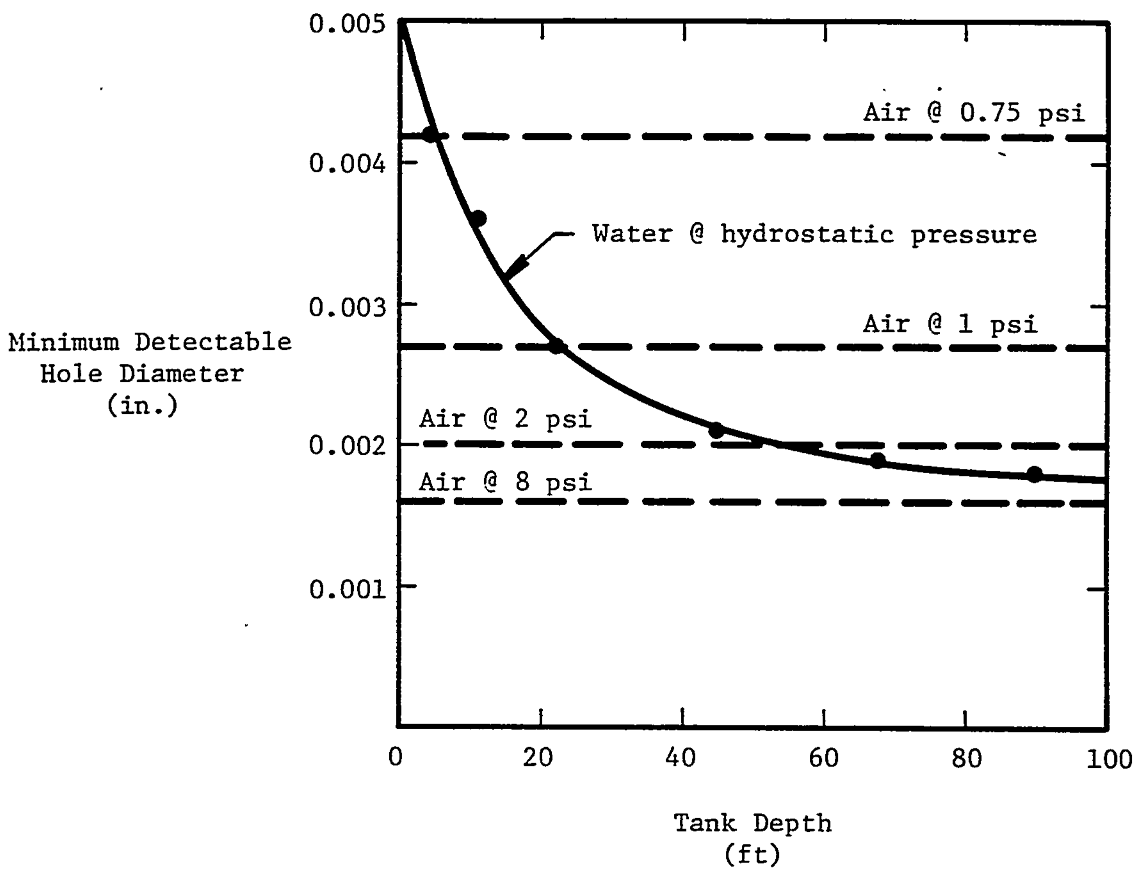
A series of welded specimens were fabricated so that further comparisons between the use of water and air (with soap) for leak detection could be made. Then specimens were assembled by joining one-quarter inch

TABLE II.7

MINIMUM DETECTABLE HOLE SIZES FOR VARIOUS PRESSURE DROPS ALONG THE LENGTH OF A STAINLESS STEEL CAPILLARY TUBE*

Hole Diameter (inch)	Minimum Pressure Drop Along Length of the Tube (psig)				
	Water**	Air & Tercetyl	Air & Leak-Tec	Air & Snoop	Air & Magic-Wand
0.0042	2.0	0.75	0.75	0.75	0.75
0.0036	5.0	1.00	1.00	1.00	1.00
0.0027	10.0	1.00	1.00	1.00	1.00
0.0021	20.0	1.80	1.50	1.50	1.50
0.0019	30.0	--	--	--	--
0.0018	40.0	--	--	--	--
0.0016	50.0	11.00	9.50	9.50	8.00

*Tube length is 0.375 in.
**Test conducted at 40°F and 80°F with similar results.



0.005
0.004
0.003
0.002
0.001
Minimum Detectable
Hole Diameter
(in.)
Air @ 0.75 psi
Water @ hydrostatic pressure
Air @ 1 psi
Air @ 2 psi
Air @ 8 psi
0
20
40
60
80
100
Tank Depth
(ft)

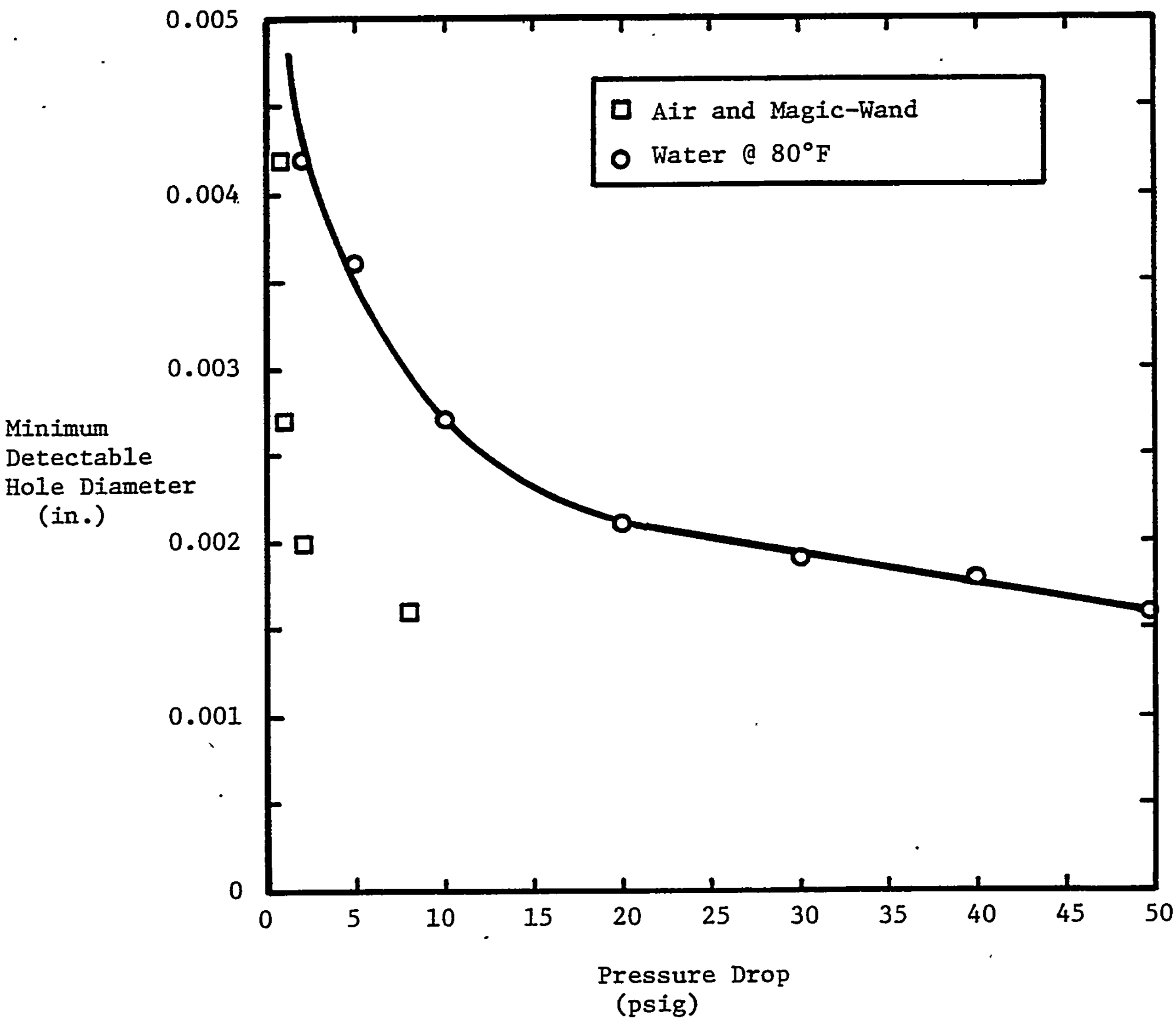


FIGURE II.6. MINIMUM DETECTABLE HOLE DIAMETER VS PRESSURE DROP ALONG THE LENGTH OF A STAINLESS STEEL CAPILLARY TUBE*

*Tube length is 0.375 in.

plates together with fillet welds as shown in Figures II.7 and II.8. The geometry of this weldment is similar to that found in wraps and collars at the penetration of longitudinals through transverse bulkheads in ship tanks. Tests on these specimens were intended to be more representative of shipboard conditions than those made with the stainless steel capillaries, and these same specimens were later used to evaluate the ability of coatings to seal weld flaws. A total of 24 welded specimens were made and tested.

All specimens were tested using water and air with soap (Tercetyl). In the search for leaks, test pressures were increased progressively to 50 psi for both the air and water tests. A total of 138 leaks were found in the weldments. All of the leaks were detected with air and soap. Nine leaks were undetected with water. These tests are more representative of ship-type flaws than the tests conducted with the stainless steel tubes, and some worthwhile comparisons between air and water can be made from the results.

Results of all tests on the weldments with and without coatings (coatings included primers and top coats) are contained in Appendix E. Some interesting results from the tests conducted before coatings were applied are summarized in Table II.8. These results show that at pressures below 5 psi, air and soap detected 127 leaks, only two less than the number of leaks detected by water at pressures up to 50 psi. At pressures up to 10 psig, air and soap detected five more leaks than the 50 psig hydrostatic test. These observations confirm the results presented on Figure II.5 which showed that air pressure in the air and soap test must be 8 psi to achieve leak detection sensitivity* equivalent to water at 50 psi.

Additional comparisons between the air (and soap) and water tests are shown in Tables II.9 and II.10. Table II.9 indicates that nine leaks were not detected by the water test. Of these, four were detected by air at 5 psig or less. Of the eleven (11) leaks which were detected by air and soap at pressures greater than 5 psig (Table II.10), five (5) were not detected at all by the water test and the remaining six leaks were detected at only high water pressures (greater than 20 psig).

The results of the tests on weldments support the data obtained using the stainless steel tubes and confirm the conclusion reached in Section II.C.3.b that for a typical ship tank, where hydrostatic pressures vary from a few psig to 50 psig, more leaks will be detected by a low pressure air test than by a hydrostatic test. This assumes that leaks are evenly distributed over the height of the tank.

D. Costs of Testing Ship Tanks

The costs of testing integral tanks on ships were reported by nine shipbuilders. In addition, one shipbuilder reported the cost of testing LNG cargo tanks, but those costs were not included in the results reported here. Testing costs were presented in different ways and for different types and sizes of ships. Six shipbuilders gave the cost for testing entire ships

*Equal detection sensitivity was obtained at observation distances of 6 inches. At observation distances of 5 ft, air and soap at 2 psig were equivalent to water at 50 psig.

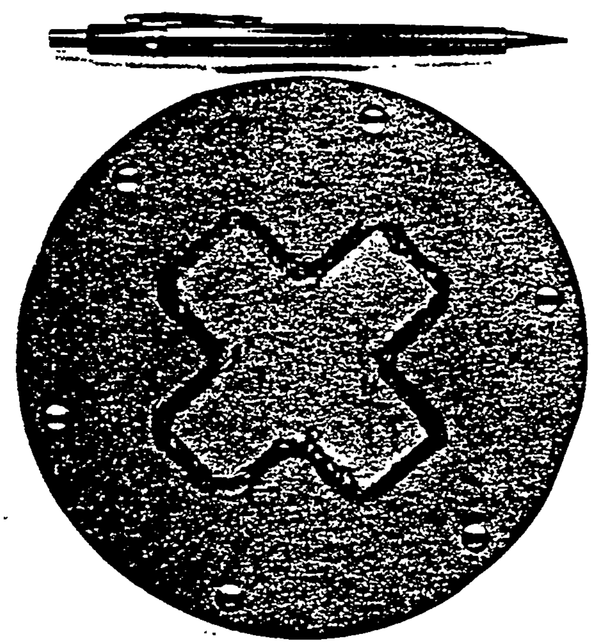


FIGURE II.7. TYPICAL WELD SPECIMEN (PLAN VIEW)

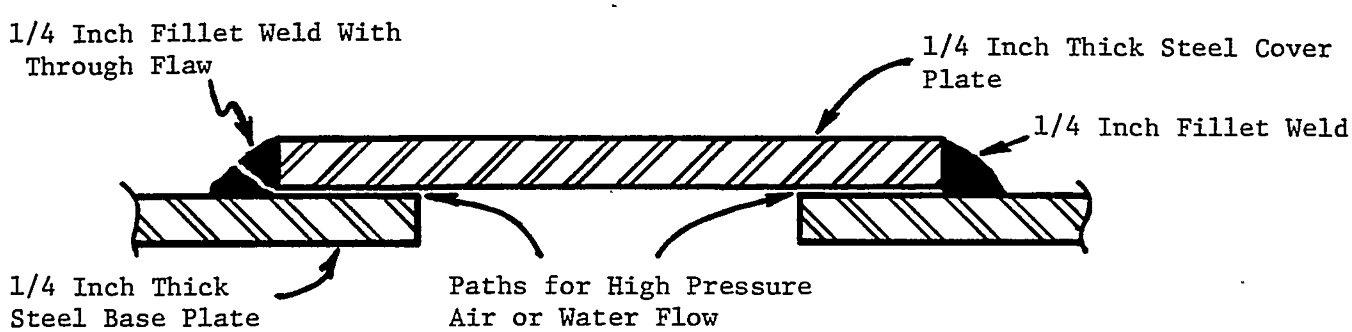


FIGURE II.8. TYPICAL WELD SPECIMEN (CROSS-SECTIONAL VIEW)

TABLE II.8

LEAKS DETECTED IN WELDMENTS BY AIR (AND SOAP) AND WATER TESTS

Pressure Level* for Leak Detection (psig)	Number of Leaks Detected	
	Air and Tercetyl Soap Solution	Water
1.0	116	103
2.0	6	6
5.0	5	5
10.0	7	5
20.0	1	4
30.0	1	0
40.0	1	3
50.0	1	3
TOTAL NUMBER OF LEAKS DETECTED	138	129

*Maximum pressure level of 50 psig

TABLE II.9

LEAKS IN THE WELDMENTS NOT DETECTED BY WATER AT 50 PSIG

Specimen Number	Air Pressure Level* for Leak Detection (psig)
1	50
2	10 10
6	5
11	40
13	1
17	1
23	5
24	10

*Maximum pressure level of 50 psig

TABLE II.10

LEAKS IN THE WELDMENTS DETECTED BY AIR (AND SOAP) AT PRESSURES GREATER THAN 5 PSIG

Specimen Number	Air Pressure Level* for Leak Detection (psig)	Water Pressure Level* for Leak Detection (psig)
1	30 50	50 ND**
2	10 10 20 10 10 10	40 40 50 ND ND 50
11	40	ND
15	10	20
24	10	ND

*Maximum pressure level of 50 psig
**ND - Not Detected

(excluding the LNG Ship) and three shipbuilders gave the cost of testing specific tanks or the cost of testing individual bulkheads.

The costs most readily compared are those for testing complete ships. Data for eight ships, provided by five shipbuilders, are listed in Table II.11. All costs were reported as man-hours and some shipbuilders noted the amount of staging and inspection fluid required. Other shipbuilders indicated that equipment was reuseable and therefore of negligible expense. Data were reported for ships which in size range from 2,400 to 350,000 dead weight tons and which include four different ship types, i.e., tanker (oil), product tanker (or product carrier), dry cargo and container. The designation 2,400 TEU container ship is unfamiliar, but it is included because it was the only container ship for which data was reported.

TABLE II.11. COSTS OF TANK TESTING

Ship Weight and Type	Man-Hours	Materials
2,400 TEU container (F)*	6,600**	-
16,000 tdw dry cargo (F)	1,500**	-
32,000 tdw product carrier (F)	2,320	-
35,000 tdw product tanker (US)	6,000	-
50,000 tdw tanker (F)	1,100	1800 planks of staging + 53 gals of inspection fluid
50,000 tdw tanker (F)	1,550	450 pieces of scaffolding plus 390 gals of soap solution
100,000 tdw tanker (F)	2,100	600 pieces of scaffolding plus 390 gals of soap solution
350,000 tdw tanker (F)	4,200**	-

*(F) denotes foreign shipbuiler; (US) denotes domestic shipbuilder.

**Not including tests during sea trials.

Man-hour levels of Table II.11 were plotted versus ship dead weight in Figure II.9 to see if costs correlate with ship size. Several shipbuilders reported that there are no basic differences in the tank testing procedure for tankers, product tankers and dry cargo vessels; therefore, data for all ships except the container ship can be grouped together. There appears to be a trend of increasing costs with ship size as might be expected; however the variation by ship type far exceeds the differences by ship size for the available data. The smallest ship in terms of weight, the container ship, has the highest testing cost. Note also that the variation for tankers at the same gross weight exceeds a factor of two (290 man-hours versus 1100 man-hours).

Because detailed breakdowns on the man-hours were not provided, it is not clear that all shipbuilders reported consistent data. For example, do the man-hours include the time of all trades involved in the testing or only time of the tank testers? The request asked for estimates of manhours, clock time, materials and facilities required for air and water testing of the cargo tanks on single bottom oil tankers in the 50-100K dwt size.

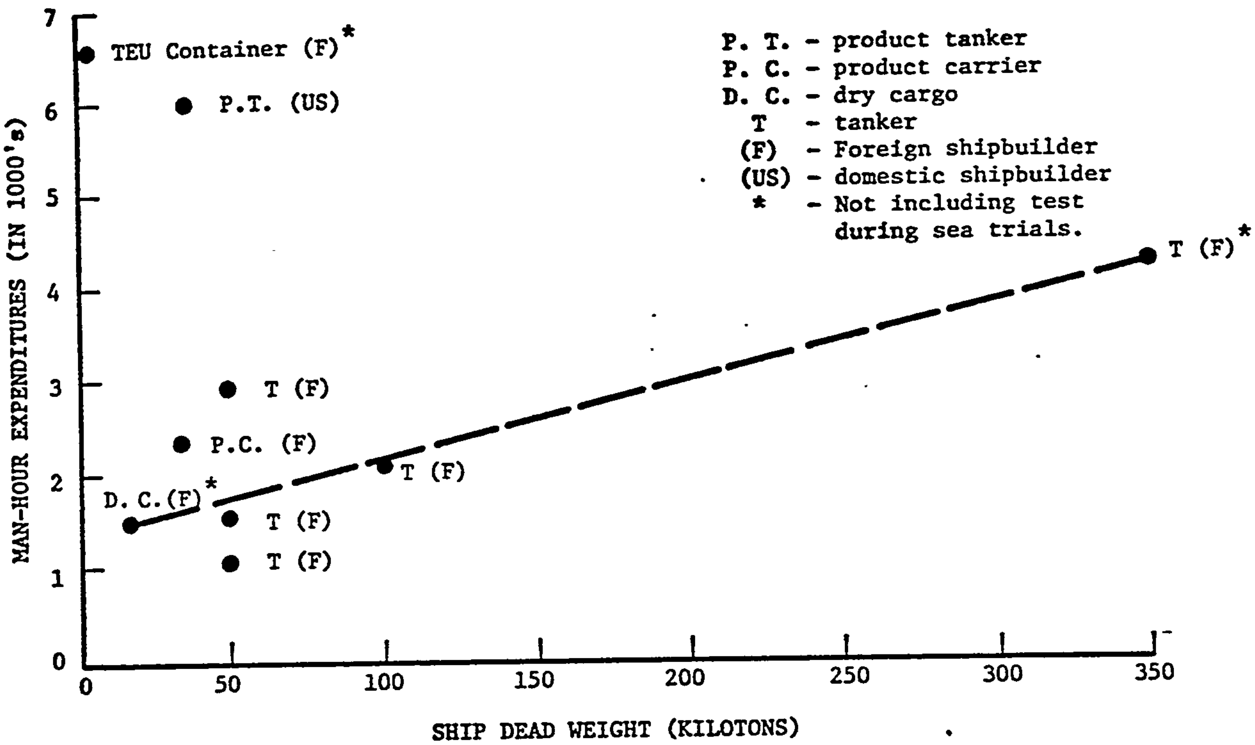


FIGURE II.9. MAN-HOURS EXPENDED IN TANK TESTING AS A FUNCTION OF SHIP DEAD WEIGHT

Consistency of replies by foreign shipbuilders implies a similar interpretation; however, the cost for testing the product tanker, reported by a U.S. shipbuilder, is very high relative to costs for similar ships reported by foreign shipbuilders. This may be caused by differences in the way costs were reported or it may represent high expenditures by U.S. shipbuilders for tank testing.

Three shipbuilders reported testing costs for individual tanks or bulkheads. Data provided is itemized below:

1.2×10^6 cu ft. oil tank (US) - 3000 man-hours

0.42×10^6 cu ft. oil tank (US) - 1600 man-hours

0.45×10^6 cu ft. oil tank (US) - 1042 man-hours

0.29×10^6 ft^3 fuel oil tank (US):
air test - 192 man-hours
hydrostatic test - 342 man-hours (incl. 160 man-hours drain time)

7750 ft^2 longitudinal bulkhead (F):
Aggregate air test - 12 man-hours
Vacuum box testing - 20 man-hours

8136 ft^3 transverse bulkhead (F):
Aggregate air test - 24 man-hours
Vacuum box testing - 44 man-hours

Erection of scaffolding (F):
Wing tank - 31 man-hours
Big axial tank (1.06×10^6 ft^3) - 44 man-hours
Small axial tank ($.53 \times 10^6$ ft^3) - 21 man-hours

Man-hour expenditures reported by one shipbuilder for testing a large oil cargo tank were based upon air testing adjacent ballast tanks and coffer-dams (standard air test plus vacuum box testing of butts and seams) plus hydrostatically testing the ballast tanks. Thus several adjacent tanks were tested to assure that the cargo tank is tight. It is difficult to estimate the cost to test an entire tanker from these per tank costs, but it is clear that costs would be much higher than those presented in Figure II.9. This also indicates that expenditures by U.S. shipbuilders for tank testing are higher than those of foreign shipbuilders. Data obtained from this survey were not sufficient to determine why tank testing costs are higher for U.S. Shipbuilders (most testing costs were provided by foreign shipbuilders); however, tightness testing of seams and joints at the subassembly stage is more common for foreign shipbuilders and this could be a factor in reducing testing costs.

III. RULES THAT GOVERN TANK TESTING

Rules that govern tank testing for integral ship tanks are summarized in this section. The edition of the rules which was used to prepare the summary are listed below. In most cases the classification societies abstracted those sections of the rules which were appropriate.

Agency	Edition
American Bureau of Shipping	1977 Rules for Building and Classing Steel Vessels
Bureau Veritas	Abstracts from Rules for the Construction and Classification of Steel Vessels
Germanischer Lloyd	Abstracts from Rules for the Classification and Construction of Seagoing Steel Ships
Lloyds Register of Shipping	Abstracts from Steel Ship Rules
Nippon Kaiji Kyokai	1977 Rules and Regulations for the Construction and Classification of Ships

ABS provided the rationale behind their rules for tank testing. This document is included in Appendix C. Also, no major differences exist between the Coast Guard rules for tank testing and those of the Classification Societies.

A. Classification Societies

The Classification Societies rules for testing integral ship tanks are remarkably similar. Important features of the rules are summarized in Table III.1. The societies require hydrostatic testing of all tanks, except those for which air testing is permitted. Usually permission to substitute the air tests must be obtained from either the local surveyor or in some cases from the home office. Hydrostatic tests, when required, may generally be performed after the application of coatings, (Germanischer Lloyd is the exception) provided the welds pass a visual inspection. The Societies apparently prefer that hydrostatic testing take place before launch. Where this is impractical, the tests may be deferred until after launch. Only Bureau Veritas permits hydrostatic testing during sea trials.

When the water tests are performed after launch, a checkerboard pattern for filling the tanks is generally allowed. This serves two purposes. First checkerboard testing permits inspection of all boundaries without having to fill each tank with water. Secondly, the pattern is chosen to provide a load distribution and draft which is representative of structural stress during service conditions. ABS allows this kind of testing for vessels longer than 750 feet. Lloyds Register requires checkerboard testing for all ships; when the test is complete, the checkerboard pattern is reversed

TABLE III.1. SUMMARY OF THE CLASSIFICATION SOCIETIES RULES FOR TANK TESTING.

HYDROSTATIC TESTS	ABS	BV	GL	LRS	NKK
Required for:	*Bulkheads separating cargo tanks from cofferdams, pump rooms, machinery spaces or tanks used exclusively for ballast are always hydrostatically tested.	*	*	*	*Double bottom, peak tanks, cofferdams and water tight bulkheads are always hydrostatically tested.
Permitted After Coatings:	Yes, provided welds have been surveyed.	Testing is allowed after application of primers. Tests may be conducted after preservative coatings if tanks have been air tested before coating.	No	Yes, provided welds have been surveyed.	Yes, provided welds have been surveyed.
Permitted After Launch:	Yes	Yes	Only when testing in berth is not practical.	No specified.	Not specified.
Checkerboard Pattern Allowed:	Yes		Yes	Yes, but after the test is completed the pattern is reversed, so all tanks are eventually filled.	Not specified.
Permitted At Sea Trials:	Not specified.	Only for cargo tanks on oil tankers.	Not specified.	Not specified.	Not specified.
Liquid Head:	See Table III.2	See Table III.2	See Table III.2	See Table III.2	See Table III.2
AIR TESTS					
Permitted For:	Double bottom, deep, oil cargo and tanks intended to carry ballast water only.	Oil cargo, wing tanks on bulk carriers.	Cargo tanks and cofferdams on oil tankers.	Cargo tanks and cofferdams. The supplementary water tests shall include at least one waterline and two side tanks.	Deep tanks, cargo oil tanks, cofferdams peak tanks.
Permitted After Coatings:	Air testing is generally done before coatings are applied. However coatings may be applied over all but manual welds prior to air testing.	Air testing is generally done before coatings are applied. However coatings may be applied over all but manual welds prior to air testing.	No	Air testing is generally done before coatings are applied. However coatings may be applied over all but manual welds prior to air testing.	No
Permitted After Launch:	Not specified.	Not specified.	No	No	Not specified.
Test Pressure:	Not specified, the air test plan is to be submitted for review.	The tank is pressurized to 3.5 psi and held for a few minutes, then the pressure is reduced to 1.75 psi and the welds examined with an appropriate inspection liquid.	Not to exceed 2.8 psi.	The tank is pressurized to 3 psi, and held for a few minutes, then the pressure is reduced to 2 psi for the inspection.	Not specified.

*All tanks are to be tested hydrostatically, except those which are permitted, at the surveyors discretion, to be air tested. When air testing is permitted, selected tanks are required to be retested with water.

and the boundaries are reinspected from the other side. The liquid head is generally different for different kinds of tanks. Liquid heads specified by each Society are summarized in Table III.2.

Air testing is permitted by the Societies on large tanks, for which hydrostatic tests are impractical. By implication, all air testing is to be performed prior to launch. American Bureau of Shipping, Bureau Veritas, Lloyds Register and Nippon Kaiji Kyokai all require that the air tests be supplemented by a hydrostatic test. One or two of each type which was air tested is then chosen by the surveyor for hydrostatic testing. If any anomalies are detected, a complete hydrostatic survey may be required. GL and NKK specify that air testing should be performed prior to the application of coatings. ABS, BV and LR permit coatings to be applied to all surfaces except manual welds prior to testing.

The procedure for air testing is not well defined in the rules. The tanks are pressurized to between 1.75 and 2.8 psi and all manual welds are inspected with a suitable inspection liquid. Two societies, Bureau Veritas and Lloyds Register require that the pressure be raised above the inspection pressure, to 3 or 3.5 psi and held for a few minutes before dropping down to the inspection pressure. ABS does not specify the test pressure, but the air test plan is to be submitted for review prior to testing. Bureau Veritas will accept alternate tank testing procedures, providing the substituted methods can be shown to be as effective in demonstrating tightness and structure adequacy as the standard testing.

B. Department of the Navy

The Department of the Navy has specific requirements for compartment testing on its ships. Two types of tests are used during construction to verify liquid tightness of compartments. These tests are called tightness and completion tests. The tests are performed after all structural work which might affect tightness has been completed.

Completion tests are designed to verify adequate tightness of a completed ship compartment designated as air tight, water tight, oil tight or fume tight. The tank is pressurized with air or liquid pressure and a lack of tightness as detected by observing a drop in air pressure or liquid head. The air pressure for water tight or oil tight compartments is 2 psi except where the structure is designed to withstand a lower pressure, in which case the design pressure is used. A compartment is considered tight providing no leakage is observed in ten minutes.

Tightness tests are designed to assure the specified level of tightness under reasonable service conditions. The tests are performed by applying water pressure equivalent to the design head of the structure. Ship tanks, cofferdams, and void spaces are subject to tightness testing. The tanks to be tested are selected by the supervisor, and should be representative of each type of tank. At least ten percent, but not less than one of each type of tank, cofferdam and void shall be tested by flooding with water to the design liquid head. If during testing, and tank shows signs of leakage, it shall be declared defective, repaired and retested. In addition, the tanks, cofferdams or voids adjacent to the defective tank shall be tested for tightness. If no tanks, cofferdams or voids are adjacent to the defective tank,

TABLE III.2. SUMMARY OF HYDROSTATIC TEST HEADS FOR THE CLASSIFICATION SOCIETIES.

ITEM NO.	WHERE APPLIED	ABS	BV	GL	LRS	NKK
1	Double bottoms	Head of water to the freeboard deck, bulkhead deck or the highest point to which the contents may rise, whichever is greatest.	Head of water to the highest of the overflow, load waterline. For compartments intended to carry fuel oil, the head shall be at least 8 feet.	Except for cargo tanks, all tanks are tested with a water head 8.2 feet above the top of the level of the load waterline, whichever is greater. The test head is to be at least to the top of the overflow or air pipe.	All tanks are tested by a head of water equal to the maximum to which the tank will be subjected, but not less than 8 feet above the crown of the tank.	Hydrodstatic test with a head of water to the top of air pipe. Where tanks are used for the same kind of oil in both sides of center girder, the center girder need not be tested.
2	Deep tanks	Head of water to the overflow, the load line or 2/3 the distance from the top of the tank to the bulkhead or freeboard deck, whichever is greatest.	Head of water to the highest of the overflow, load waterline or 0.3 H above the compartment top. In any case 0.3 H shall be greater than 3 feet but less than 8 feet.	See Item 1.	See Item 1.	Hydrostatic test with a head of water to the top of overflow pipe, or to the level of 8 feet above the tank top, whichever is the greater.
3	Cargo oil tanks and cofferdams of oil tankers	To a head of water (specified below) above the deck at side forming the crown of the tanks. In no case shall the test head be less than the distance to the top of the hatch.*	Head of water above the deckline at side equal to the lesser of 0.065L or 8 feet. Where testing is carried out during sea trails, the waterhead may be limited to the cover level.	Head of water 8.2 feet above the top of the tank. For cofferdams, a head of water up to the top of access opening is adequate.	The test head for cargo tanks is 8 feet above the highest point of the tank, excluding hatchways. For cofferdams, the test head is to the top of the hatchway.	Hydrostatic test with a head of water to the level of 8 feet above the deck at side forming the crown of the tank or to the level of the top of hatch, whichever is the greater.
4	After peaks and stern tube compartments	See Item 2.	Peak tanks used for ballast are to be tested as in Item 2. Testing of the aft peak is to be performed after fitting the stern tube.	See Item 1.	See Item 1.	Hydrostatic test with a head of water to the load waterline. Where they are used as tanks, tests are as specified in Item 2.
5	Fore peaks	See Item 2.	Peak tanks used for ballast are to be tested as in Item 2.	See Item 1.	See Item 1.	See Item 4.

*Length (ft)	Head (ft)
0-200	4
200-400	4 + (L-200)/50
400 and above	8

then at least one other space in a location similar in construction to the defective space shall be tested for tightness.

IV. CONSTRAINTS ON NEW TEST METHODS

New test method for testing integral ship tanks must be acceptable to shipbuilders, ship owners, regulatory agencies and classification societies. Each of these parties or agencies shares some concerns and each has its own unique requirements. In general, the principal concerns of each party appears to be:

Shipbuilders: productivity in shipbuilding
Regulatory Agencies: safety and the environment
Classification Societies: ship strength and seaworthiness
Owners: all of the above

In terms of tank testing, shipbuilders want to build a tight, sound tank but they want to do it cheaply and quickly. Regulators and classification societies must be able to determine whether or not the tank is tight and strong. Owners must be concerned about both.

To meet these requirements, certain constraints must be placed on the test methods and certain goals should be set. Constraints have been divided into regulatory constraints and practical constraints. Regulatory constraints are set principally by requirements of the regulatory agencies and classification societies but they may also be required by and/or benefit shipbuilders. Practical constraints relate primarily to productivity. Finally, criteria for acceptance are defined which combine the constraints and goals for a new tank testing method.

A. Regulatory Constraints

1. Tightness Testing

Regulators and classification societies have not set leakage standards for integral ship tanks or criteria for leak detectability. Thus, to establish criteria for a new test method, current test methods must serve as a guide. Two tests, the standard air test and the hydrostatic test, are accepted by regulators and classification societies for tightness testing of ship tanks; however, there is considerable variation in the degree of acceptance of air testing (see Section III). For example, some classification societies accept the air test as a final tightness test only for oil cargo tanks. All other tanks must be hydrostatically tested along with selected cargo tanks. Several societies also call for tightness testing (air or hydrostatic) before coatings are applied to the welds. Others require an air test before coating if subsequent hydrostatic tests on the same tank are to be performed after coatings. The majority of classification societies will permit air testing of all tanks (prior to coatings) as a tightness test, with selected tanks then subjected to a hydrostatic test (after launch and after coatings) to check both tightness and strength.

Only ABS rules explicitly define when the hydrostatic test is a tightness test and when it is a structural test. A hydrostatic test is considered as a structural test only for oil tankers greater than 750 ft in length. For all other vessels it is a tightness test, and it is required because of a lack of confidence in the air test.

Two sets of criteria can be established for new test methods. One set is based upon the air test and one set is based upon the hydrostatic test. Two sets of criteria, so determined, are given below. Because of productivity considerations the new test method will be air-based.

Criteria Based on the Standard Air Test

Sensitivity: 10^{-3} - 10^{-4}* atm-cc/sec (equal to air and soap)

Leak Location: Leaks visible from 6" - 24" with adequate lighting.

Safety: Test pressures limited to 2.0 - 3.5 psi range. Same safety precautions against overpressurization as for the standard air test. Air additives must be safe and adhere to those sections of the OSH Act which pertain to shipbuilding and ship repair.

Criteria Based on the Hydrostatic Test

Sensitivity: 10^{-3} - 10^{-5}* atm-cc/sec (equal to water at pressures up to 40 psi)

Leak Location: Leaks visible from distance of several feet with a strong light source, although close inspection (6" - 24") may be required to distinguish small leaks from condensation.

Safety: Test pressures limited to 2.0 - 3.5 psi range, with precautions against overpressurization, to assure same level of safety as with the standard air test. Air additives must be safe and adhere to those sections of the OSH Act which pertain to shipbuilding and ship repair.

To develop an air-based test which satisfies the above criteria for the standard air test should not be difficult; however, it may be difficult to do so if the principal constraint is improved productivity. To develop an air-based method which satisfies the above criteria for the hydrostatic test will be more difficult. Even for this case, practical constraints, such as cost and test time may be the governing factors. It is certainly possible to find air-based methods which at 2.0 psig pressure will equal the sensitivity of water at 40 psig; but, because of cost, bulky equipment, etc., these methods may not be practical for tank testing.

The effects of coatings are not included in the aforementioned criteria. As for the air and soap test, any air-based test would probably be performed before the application of coatings. This is a very important factor in shipbuilding and has been investigated in Phase II (see Section VII) of this program.

*Definition of sensitivity is given in Section V.

2. Structural Testing

As stated in Section II.C.2 neither the hydrostatic test nor the 2.0 psig air test subject the tank structure to its design loads. Thus, neither test should be referred to as a structural test of the tank.

3. Training and Safety

Training and safety, as discussed here, relate to equipment used in the testing procedure. Both inspectors and surveyors contacted in the survey objected to the carrying of equipment in the leak detection process. They believed that even light portable equipment can be dangerous because wires (to earphones, etc.) can catch on tank internals. Under some conditions this could cause an inspector to fall from dangerous heights. Also, inspectors were concerned that any equipment would be very cumbersome in tight places such as some double bottom tanks on barges or Navy ships.

Not only is the physical presence of the equipment objectionable, but training in the use of equipment might be a problem. U.S.C.G. inspectors contacted expressed the opinion that frequent duty assignment changes within the Coast Guard make training particularly difficult for them. They object to anything beyond visual inspection for leaks. Assignments of ABS surveyors appear to be longer, and so their training in the use of specialized equipment presents less of a problem.

In summary, surveyors and inspectors do not want to be encumbered with equipment or trained in its use; however, these objections do not necessarily reflect the official position of ABS or the U.S.C.G. New methods, which significantly improve on current procedures, would probably be accepted even if special equipment were required.

B. Practical Constraints

Practical constraints are those associated with ship productivity. New testing methods which do not equal or improve upon current methods in most aspects of the testing procedure, will not be accepted. For example, a new test method should minimize:

1) test time
2) manhour expenditures
3) training of personnel
4) cost of expendibles
5) equipment depreciation costs
6) disruption of schedule
7) anything that adversely affects the work of other trades

Although objectives of a new test procedure will be to minimize each factor, the aggregate cost to the shipbuilder will determine the acceptance or rejection of the method.

Based upon the evaluation of current methods in Section II.C, it is clear that hydrostatic tests cause many problems in ship construction and some problems in inspection. Conversely, air tests cause many problems in inspection but few in construction. Therefore, if the goal is to improve productivity, the new test method must be air-based. Air-based methods reduce items (6) and (7) relative to hydrostatic testing. Thus, an air-based test, which is fully acceptable* to regulators in lieu of a hydrostatic test, would reduce hydrostatic testing and could improve productivity.

Even if an air-based test cannot be found to replace the hydrostatic test for tightness testing, improvements in productivity can be achieved by improving items (1) through (7) relative to the pre-hydrostatic air test. A method is sought which is faster, cleaner and can be used at different stages of construction. Such a method could replace current air testing, with resulting gains in productivity, even though hydrostatic testing is still required by the regulatory agencies.

It may not be practical to seek a single test method which replaces both the air and soap test and the hydrostatic test for tightness testing. The air and soap test is used principally by the shipyard to aid in producing a tight tank. The hydrostatic test is used primarily for demonstrating tightness and/or structural strength to the inspectors and surveyors. Following this approach to tank testing leads to somewhat different requirements for the two tests. A replacement for the air and soap test emphasizes productivity, with adequate sensitivity to assure a tight tank. A replacement for the hydrostatic test emphasizes high visibility of leaks and sensitivity equal to the hydrostatic test. Direct costs of the latter test may be high, but if it is air-based and can replace the hydrostatic test for tightness testing, overall gains in productivity will be achieved.

C. Criteria for Acceptance

Based on the regulatory and practical constraints discussed above, criteria for acceptance have been formulated for two different air-based tightness tests. One test can be regarded as a replacement for the standard air test and one as a replacement for the hydrostatic test. As stated under Practical Constraints, it is possible but not probable that a single test can

*Requires no subsequent hydrostatic testing for tightness, even on a sampling basis.

be found which satisfies both sets of criteria. The strong emphasis on leak visibility for the "substitute hydrostatic test" eliminates potential methods, which rely upon sensing equipment (see Section V) from consideration. Thus, high visibility may be gained with some sacrifice in productivity. For this reason, a separate test, which can be referred to as a substitute for the air and soap test, will be sought which has no such restrictions. One goal will be to extend the distance from the structure for leak detection, but detection may not be visual. Emphasis for the air and soap substitute test will be productivity. A summary of the criteria for each method is given below.

Replacement for Hydrostatic Test

Sensitivity: 10^{-3} - 10^{-4} atm-cc/sec (equal to water at 40 psig)

Leak Location: Leaks must be visible. Visibility equal to or greater than with water. Leak location from a distance of 50 ft from the structure is a goal. If entire tank boundary is not tested simultaneously, it must be obvious which parts have been tested. Semi-permanent leak indication is desirable.

Safety: Must be as safe as current air test. Safeguards must be used to prevent overpressurization. Chemical used must satisfy sections of the OSH Act which pertain to shipbuilding and ship repair. Minimum or no equipment required for inspection by inspectors or surveyors.

Productivity: Overall productivity with the new test method must exceed that with the hydrostatic test.

Replacement for Standard Air Test

Sensitivity: 10^{-3} - 10^{-4} atm-cc/sec (equal to air and soap)

Leak Location: Leak detection and leak location must be superior to air and soap. Leak detection from a distance of 50 ft is a goal. Visible leak detection is not a requirement.

Safety: Must be as safe as or safer than current air test. Chemical used must satisfy sections of the OSH Act which pertain to shipbuilding and ship repair. Equipment must be light and portable and not unnecessarily cumbersome to the tank testor.

Productivity: Productivity must be improved over the standard air and soap test. Method should be suitable for testing at different stages of ship construction.

V. A SURVEY OF LEAK DETECTION METHODS

A. General Description

There are three types of leak detection: leakage measurement, leak location and leakage monitoring. Leakage measurement is used to determine the extent of leakage from a closed system. This method is commonly used to determine if a leak exists, and if it exists, how severe the total leakage is. Leak location is obviously the process of determining the exact position of individual leaks. Leakage monitoring is the continuous monitoring for the presence of contaminates within a system. The major differences between leakage monitoring and the other types of leak detection are that monitoring is performed over extremely long periods of time, the equipment is smaller and consumes less power. During the literature survey portion of the program, many types of leakage testing techniques were investigated. These methods are listed in Table V.1 where they are grouped according to operating principle. An indication of the most common mode of application, i.e., measurement, location, or monitoring, is also provided. In the sections which follow, leak location methods which appear to be applicable to ship tank tightness testing will be described in some detail.

Throughout this report, leakage rate is expressed in the units of atm-cc/sec. This expression is derived from the Ideal Gas Equation which is:

$$n = \frac{PV}{RT}$$

where n = number of moles

P = pressure

V = volume

R = Universal Gas Constant

T = temperature

The number of moles is directly proportional to the pressure times the volume when the temperature is assumed to be a constant. By dividing the number of moles by time, a leakage rate is calculated. The units for pressure multiplied by volume divided by time may be represented by atmospheres multiplied by cubic centimeters divided by time (or atm-cc/sec)*. The sensitivities of the following leak detection methods have been compared on this basis.

B. Chemical Indicators

The chemical indicator procedure consists of leak location by visually detecting the presence of a color in the vicinity of a leak. There are two general classes of chemical indicators: chemical reaction and penetrants. The color indication for the chemical reaction technique is due to the reaction of a leaking tracer gas with a developer. In the penetrant technique the color is inherent to the penetrant.

*In engineering work, leakage units of atm-cc/sec are generally considered standard units. Because relative sensitivities are of interest, units are not important but they must be consistent.

TABLE V.1. POTENTIAL TANK TESTING METHODS

Technique	Application		
	Measurement	Location	Monitoring
Chemical			
Dye Activation		X	
Penetrants		X	
Tracer			
Mass Spectrometer	X	X	
Halogen	X	X	
Light Absorption	X	X	
Thermal Conductivity	X	X	
Smoke		X	
Catalytic Combustion			X
Flame Ionization			X
Electrochemical Cell			X
Acoustic			
Sonic		X	
Ultrasonic		X	
Acoustic Emission		X	
Other			
Laser Excited Interferometry		X	
Liquid Crystal		X	
Radioactivity	X		X
Halide Torch		X	

The chemical indicator procedure is a static technique. Therefore, the longer a test is run, the more sensitive it becomes. The results are not quantitative because the response is the size and the color intensity of the leak. The estimated sensitivity of the chemical reaction technique is about 10^{-3} atm-cc/sec; the sensitivity of penetrants is thought to be several decades better(1).

1. Penetrants

Weld inspection with penetrants is dependent on the ability of certain liquids to enter into voids and crevices by capillary action. Penetrant inspection is widely used in the fabrication industries for the detection of very small weld flaws(2,3) or imperfections, and somewhat less frequently for the detection of leaks(4,5,6,7). There are two basic types of penetrants, one is a visible dye and the other is fluorescent under ultraviolet light. Some of the commercially available penetrants are listed in Table V.2. The basic procedure for using penetrants is independent of the penetrant type and consists of the following steps: precleaning, application of the penetrant, dwell period, application of a developer, examination and postcleaning.

Commonly used fluorescent penetrants are manufactured commercially and have low surface tension, low viscosity and good visibility. These properties make fluorescent penetrants ideal indicators for leak location. For improved sensitivity, excess material such as slag, scale, grease or paint should be removed before application. Then the penetrant is either brushed or sprayed on the weld surface to be inspected. Depending on the material and the type of penetrant used, a dwell time sufficient to allow the penetrant to enter and penetrate through the small cracks is required. If a developer is used, it is sprayed or brushed onto the opposite side of the weld from which the penetrant was applied. The developer must be applied in a thin coat to avoid masking very small indications. It may require a dwell time of about 5 to 10 minutes before the examination. The weld should be examined under a strong ultraviolet lamp from a distance of not more than three feet, in a darkened area or enclosure. Indications of leaks will glow brightly and contrast sharply with the background when viewed with an ultraviolet lamp. Fluorescent penetrants are generally water soluble so cleanup is relatively simple and straight forward.

The sensitivity of liquid penetrants is about the same as the air-based soap tests for leak location. The advantage of liquid penetrants is that the indication is more visible - a color change or a glow when viewed under an ultraviolet lamp. The indication is also more permanent; it will remain until the surface is washed down. The disadvantages are that the test materials are more expensive than soap, materials are usually applied to both sides of a weldment (to improve sensitivity) and lastly, the time required to obtain an indication, even when pressure is applied, may exceed several hours. Liquid penetrants do not appear to be a suitable technique for testing large tanks or ships. Applications may include leak testing on leak prone subassemblies or perhaps in conjunction with the vacuum box technique. This would be attractive only because a relatively permanent leak indication is provided by the penetrant.

TABLE V.2. COMMERCIALLY AVAILABLE PENETRANTS

TRADE NAME	MANUFACTURER	INTRINSIC COLOR	REQUIRES DEVELOPER	FLUORESCENT	COLOR
Fluoro-finder FL-50	Testing Sys. Inc.				
Chex-All	Ritter Chemical	X	X		Red
Various	Spectronics		X	X	
DUBL-Chek	Sherwin, Inc.			X	
Tracer Tech	Shannon Luminous			X	
MET-L-Chek			X		Red on white back-ground
Zyglo Penetrex }	Magnaflux			X	
Zyglo }			X	X	
Trace	Highside Chemicals				Red

2. Chemical Activation

Tank testing with the chemical reaction technique is not as standardized as with the chemical penetrant technique. This method depends on the diffusion of a trace gas from the inside of a tank to the outside where it reacts with a chemical developer on the exterior surface. The chemical reaction results in a discoloration of the developer which may be visible or may require ultraviolet light to be visible. This method has apparently not been applied to leak location on integral tanks, perhaps because of the cost of the chemicals. Several trace gases were identified during the literature survey, only one of which is marketed specifically for leak location(1,7,8). The trace gases and the associated chemical developers which were identified are listed in Table V.3. Of the chemical reaction systems listed in the table, only four appear to be practical for testing large tanks. The ammonia-phenolphthalein and titanium oxide and the carbon dioxide and agar-agar systems appear suitable since the developer may be applied to the test article conveniently. In addition the leak indicator is a bright color, easily visible against the contrasting color of the unreacted developer. The carbon monoxide-palladium chloride system is also attractive because it has good visibility; however, a convenient method to apply the developer to the test article remains to be developed. These three methods are not well described in the literature. No procedure for determining the required concentration of the tracer gas is provided, nor is any indication of the sensitivity of the system given.

The Tracer Tech chemical reaction system was the only commercially available system identified during the literature search. With this method the surface to be examined should be reasonably clean. Then X-205 barrier fluid is sprayed over the test area. The thin coating contains a white pigmentation which dries to a grease-like film. This film is required to prevent chemical or electrochemical activation of the sensitive developer. The T-621 developer has a pale blue color and may be applied over the barrier film by brushing or spraying. Bright red spots are produced in the developer when contacted by the tracer gas. For maximum sensitivity, X-206 masking fluid may be applied over the developer. The tracer gas is an organic amine which is supplied as a X-207 vapor source. In use, the vapor source is exposed to the flow of air which is pumped through the leaks. The vapor fumes obtained in this manner are sufficiently strong to trigger the sensitive T-621 tracer, while at the same time not producing a personnel hazard. Leaks which are undetectable with soap film tests are reported to be readily detectable with the Tracer Tech chemical reaction system(9).

The capability of chemical reaction systems to detect leaks is potentially as good as air-based soap tests. The primary advantage of these methods is the highly visible and relatively permanent leak indicator. The developer may be sprayed onto the test surface and it generally will remain reactive even after drying. Since the developer is colored, it is easy to determine if it has been applied properly. The primary disadvantage of this method is the cost of the materials. In addition, except for the Tracer Tech system, the procedures for applying the method are not very well defined. Finally, the Tracer Tech system is cumbersome since as many as three different films must be applied to the surface being tested to obtain the maximum sensitivity.

TABLE V.3. CHEMICAL REACTION SYSTEMS USED FOR LEAK LOCATION

TRACE GAS	DEVELOPER	INDICATION	APPLICABILITY	COMMENTS
Ammonia	**0.1N HC1**	Fumes	Poor	Developer is applied to swabs which are held near suspected leaks.
Ammonia	Phenolphthalien and Titanium Oxide	Pink Discoloration on White Background	Good	Developer may be painted on surface.
Ammonia	Bromocresol Purple	Purple Color	Poor	Developer is applied on paper which is held near suspected leaks.
Carbon Dioxide	Agar-Agar	Turns From Red to White	Good	May be sprayed on test article.
Nitrous Oxide	Starch Iodide	Color Change	Poor	Requires relatively long dwell times.
Carbon Monoxide	Palladium Chloride	Brown Discoloration on White Background	Good	Developer is impregnated into tape which is applied to the weld.
X-207 Vapor* Source	Tracer Tech* T-621	Bright Green Under Ultraviolet Light	Good	Requires a Three Layer Developer

* Manufactured by Shannon Luminous, Los Angeles, California

C. Tracer Gas Detectors

Four tracer methods are described in the following subsections. The methods all involve the pressurization of a tank usually with a mixture of air and a tracer gas. Then diffusion of the tracer gas through flaws in the welds are detected with an electronic device. The presence of a leak is indicated by an audible tone, a meter deflector or a flashing lamp. The accuracy of these methods depends primarily on the uniform dispersion of the trace gas within the volume being tested. Therefore, the method of introducing the trace gas into the system should be carefully considered. In a study for NASA(10), slug injections of helium and freon resulted in nonuniform dispersal of the tracer within the system. This report recommends premixing of the trace gas and air prior to injection into the system. Another factor which contributes to the sensitivity of the tracer methods is the concentration of the tracer within the system. Obviously, the higher the concentration, the greater the sensitivity. For economic reasons, the trace gas concentration is usually 1% by volume when testing large systems.

The technique for locating leaks with these tracer methods is known as the sniffer technique. The test item is filled with the tracer-air mixture to a pressure greater than atmospheric. The welds of the test article are scanned with a "sniffer" connected to the instrument. Any tracer flowing out through cracks or pinholes will be drawn through the sniffer probe, into the instrument by a vacuum system. The presence of a large amount of tracer in the air surrounding the test article may mask indications and locations of leaks. For this reason, it is important to locate any large leaks before performing a systematic scan of the vessel. For trace gases lighter than air, the scan should progress from the bottom of the test article to the top. For gases heavier than air the scan should be performed in the reverse order. As leaks are located, they should be repaired or plugged before continuing the test.

1. Mass Spectrometer

Mass spectrometry is probably the most commonly used leak detection procedure. This instrument is produced by many manufacturers, and has a sensitivity for helium of 10^{-11} to 10^{-14} atm-cc/sec (0.1 ppm helium in air). The ultimate sensitivity quoted by manufacturers is usually based on a 100% trace gas concentration; the sensitivity obtained in actual testing with 1% helium will be correspondingly lower(11).

The mass spectrometer ionizes molecules and separates them in terms of their mass in a magnetic or electromagnetic field. Detection and measurement usually consist of observation of the intensity of the ion current in the spectrometer tube. Because a vacuum is necessary for operation of the mass spectrometer, leak detection using this technique involves the use of a high vacuum system. For this reason, mass spectrometer leak detection systems are rather large, massive and relatively complex pieces of equipment. The mass spectrometer will respond to the presence of any tracer gas. However, helium is usually used in leak location applications since it is inert, and will not react with other gases and materials in the system. Helium is not present in the atmosphere in any significant quantitites. Helium is a small molecule and will pass through small leaks more readily than heavier gases. The physical characteristics of the mass spectrometer, and its sensitivity with helium as the trace gas are summarized in Table V.4.

TABLE V.4. GENERAL CHARACTERISTICS OF THE MASS SPECTROMETER LEAK DETECTOR

TRACE GAS: Helium - most common, hydrogen, argon, neon and butane are also used.
MINIMUM RECOMMENDED TRACER CONCENTRATION: 1% by volume
SENSITIVITY: 1×10^{-11} to 5×10^{-14} atm-cc/sec with 100% helium
POWER REQUIREMENTS: 115 VAC at 1000-2000 watts
WEIGHT: 200-600 lbs
REQUIRED ACCESSORY: Liquid Nitrogen

Helium diffuses rapidly in air, therefore a steep helium concentration gradient exists in the vicinity of a leak. The mass spectrometer probe senses the tracer concentration only at the probe opening. If the probe misses the leak by as small a distance as 0.25 in., the sensitivity drops by 10 to 1. To overcome this problem, a small rubber cup is sometimes placed over the end of the probe. While this solves the problem of proximity, it also creates a time constant problem. When the cup passes over a leak it begins to fill with helium. The probe is continually monitoring the helium concentration in the cup. After a time, the helium concentration will reach equilibrium and the full mass spectrometer sensitivity will be attained. However, the time constant is about a half hour, and the probe is only over the leak for a few seconds. So during tank testings this problem is not likely to occur. The probing speed as well as proximity is critical. At a probing speed of 3 ft/min., even under ideal conditions, the probe must be within 1/4 in. of the leak to be detected. If the weld being inspected is wider than 1/4 in. two parallel passes must be made to ensure that all leaks are detected.

The mass spectrometer has the greatest sensitivity of any of the leak detection methods identified during the literature survey. However, the physical size of the equipment, the relatively short "sniffer" probe, and the problems with proximity and probing speed exclude mass spectrometry from consideration as a leak detection device for general tank testing by the shipbuilding industry.

2. Halogen

The halogen detector is quite similar to the mass spectrometer, with only the means of detection differing. The basic components of a halogen detector are the sniffing probe, vacuum system, and detector. Generally halogen detectors are more portable than mass spectrometers; some may be handheld. The detector uses a glowing hot platinum or ceramic filament which emits positive ions. The presence of trace amounts of halogen vapors stimulates the emission of ions. The amount of ionic emission is measured to indicate the presence and relative size of leaks. A meter deflection and an audible sound are used to indicate the presence of halogen vapors to the operator. The maximum sensitivity of the halogen detector is on the order of 10^{-9} atm-cc/sec[1] (with 100% tracer). To reliably detect leaks on the order of 10^{-5} atm-cc/sec, the probe speed should not exceed about 2 in./sec. Physical characteristics of the halogen leak detectors are listed in Table V.5.

TABLE V.5. GENERAL CHARACTERISTICS OF THE HALOGEN LEAK DETECTOR

TRACE GAS:	Freon-12 or Freon 22 - most common; also compounds containing iodine, chlorine and fluorine
MINIMUM RECOMMENDED CONCENTRATION:	1% by volume
SENSITIVITY:	1 x 10^{-5} to 1 x 10^{-9} atm-cc/sec with 100% Freon
POWER REQUIREMENTS:	Handheld unit - 1.5v batteries Standard unit - 115v, 100 watts
WEIGHT:	Handheld unit - 1.5 lb Standard unit - 15 lb + 2.5 lb for probe

The most common halogen tracers contain chlorine, although those containing iodine, bromine and fluorine may also be used. Freon-12 and Freon-22 are the most common halogen tracers. Note that these tracers are all high molecular weight compounds. For example, Freon-12 (Cl_2F_2C) has a molecular weight four times that of air. This implies that uniform dispersion of the trace gas through the system may be difficult to attain. For small chambers the halogen tracer may diffuse throughout the system in 30 minutes[12], but for large complex systems uniform tracer dispersal may not be achieved after 24 hours[10]. Also the relatively large tracer molecules will not diffuse through very small cracks as easily as helium. During inspection, care should be taken to ensure a clean air environment as the halogen leak detector will respond to smoke and paint, fumes, as well as halogen gas. Since the detector element operated at 1600°F and with a voltage of 300v, inspection should never be performed in areas containing an explosive vapor.

The halogen detector is a sensitive device which has been used for many years to locate leaks. Freon, which is commonly used as the trace gas, is nonflammable, noncorrosive and does not present a personnel hazards. The halogen detector may be purchased as a lightweight, easily portable unit. However, the slow probing speed and the high sensitivity to "foreign" particles makes the halogen detector undesirable for testing integral ship tanks.

3. Light Absorption

A tracer gas which absorbs radiations of a particular wave length is used in the light absorption procedure. The presence of a tracer is indicated by the reduction of transmitted radiation of a given wavelength. Ultraviolet radiation may be used, but infrared is more common. The detector consists of a radiation source, a reference cell, a sample cell, sniffing probe and a vacuum system. Radiation passing through the sample cell is compared to that passing through the reference cell. General characteristics of the light absorption leak detectors are given in Table v.6.

TABLE V.6. GENERAL CHARACTERISTICS OF THE LIGHT ABSORPTION LEAK DETECTOR

	Infrared	Ultraviolet
TRACE GAS:	Nitrous oxide, Carbon dioxide	Chlorinated & aeromatic hydro-carbons
SENSITIVITY:	1×10^{-6} atm-cc/sec	5×10^{-5} atm-cc/sec
POWER REQUIREMENTS:	l15v, 200 watts	115 VAC, 160 watts
WEIGHT:	60 lb	30 lb

Many of the units on the market have response times on the order of 5-30 seconds. These units are generally used in leakage monitoring applications. Other units have response times on the order of 1 to 3 seconds. These units may be used for leak location; however, the probing speed may not be any better than for the mass spectrometer or halogen leak detectors. Since the sensitivity of the light absorption leak detector (about 1 x 10-6 atm-cc/sec with 100% tracer) is lower than with the other two tracer methods, and the scan rate is not better, this methods is not considered to be an acceptable leak location procedure for general ship tank testing.

4. Thermal Conductivity

The thermal conductivity method is similar to the light absorption leak detector. In this case the tracer must have a thermal conductivity different than air. The detector consists of a thermistor bridge which responds to the different thermal properties of the tracer laden gas passing over half of the bridge, and clean air passing over the other half. output of this thermistor bridge is measured to indicate the presence of a leak. Typical tracers for thermal conductivity leak detectors include helium, hydrogen, Freon, carbon dioxide, ammonia, argon and neon. Generally, the lighter tracers are chosen to maximize diffusion rate and the ability to penetrate small defects. Thermal conductivity leak detectors are generally as portable as halogen detectors, but are not as sensitive. General characteristics of these detectors are summarized in Table V.7. The primary disadvantage of the thermal conductivity method is the lack of selectivity. The detector will respond to almost any impurity in the air, making it an unacceptable leak detection technique except under the most ideal circumstances.

TABLE V.7. GENERAL CHARACTERISTICS OF THE THERMAL CONDUCTIVITY LEAK DETECTOR

TRACE GAS:	Helium, hydrogen, Freon, carbon dioxide, ammonia, argon and neon
SENSITIVITY:	2×10^{-4} atm-cc/sec
POWER REQUIREMENTS:	1.5v batteries for portable unit 115v, 100 watts for standard unit
WEIGHT:	4 lb for portable unit 20 lb for standard unit

D. Acoustic Sensors

One method of gaseous leak detection in a pressurized system detects the acoustic emission - the sound - caused by escaping gas. As gas escapes through an orifice, both sonic and ultrasonic energy are produced by the turbulence that occurs in the transition from laminar to turbulent flow. This energy provides a detectable and measurable quantity that makes for a practical leak detector. The acoustic leak detectors may be divided into three categories according to the frequencies which are monitored: sonic (20-20,000 Hz), ultrasonic (40-60 KHz) and acoustic emission (100 KHz). In addition, there are two techniques for using the detectors: active and passive. In the active technique, sound is injected into the tank being tested, usually in conjunction with moderate tank pressurization. The passive technique involves only pressurization of the tank. In either case, inspection with the acoustic leak detectors is generally conducted from the outside of the tank. The operator stands some distance (10-50 ft) from the panel being inspected and systematically scans the welds. The amount of acoustic energy striking the detector is displayed on a meter, and an audible tone is produced.

The advantages of the acoustic method are that no tracer gas is required, and, providing the leak rate is high enough, detection may occur at distances of up to 50 ft. Disadvantages include the possibility of ambient noise drowning out the sound of the leak, and the fact that acoustic energy is easily reflected by hard surfaces. This means that the operator must learn to differentiate between direct and reflected sounds.

1. Sonic

Audible frequency leak detection devices have been developed for leak location on buried pipelines([13,14]). In these tests a section of pipewhich is known to have a leak is blanked off and pressurized. The leak is located by moving a transducer through the pipe until the maximum signal is detected. The majority of sonic energy was found, to be in the 50-5000 Hz range. Leaks were found with good accuracy with this technique. However, the tests were conducted in open country, with few sources of noise in. the audible frequency range. In a shipyard environment many noise sources exist in this frequency range., so the probability of masking the sound of small leaks is high. Therefore, the sonic detectors were not considered any further.

2. Ultrasonic

For gross leaks, the sonic detector may be suitable but smaller leaks require a more sensitive instrument. The use of an ultrasonic detector changes this from a gross leak method into a fine one while the extension of the frequency range into the ultrasonic increases the system sensitivity still further. Commercially available ultrasonic detectors restrict their response to the ultrasonic range and reject the audio frequency band altogether.Generally these probes operate in the range of 40 KHz, although the actual emission from a leak reaches up to 60 KHz(15). The probe converts the frequencies heard within its detection band down to the normal range of human hearing. The probe operator searches for leaks by "listening" with the probe with much greater sensitivity and at a much higher range. Because the audio frequencies are rejected, loud background noise in that range has no effect. The maximum sensitivity of the ultrasonic leak detectors is on the order of 10-4 atm-cc/sec. Generally, the sensitivity of these devices is quoted as the maximum distance at which a given size leak may be detected. For example, one unit is said to be capable of detecting leakage from a 5 mil diameter hole, under 5 psi pressure, from 30 ft away([16]).

One report identified during the literature survey described the use of ultrasonic detectors to locate leaks in ship tanks during construction. At Swan Hurter Shipbuilders, Ltd., a Dawe Ultrasonic Leak Detector was used to inspect the welds on all tank compartments on a 250,000 dwt oil tanker. The tests were carried out at night to take advantage of reduced shipyard noise. The complete survey of a tanker section required about half a day, which reportedly compared favorably with inspection with soap.

Leak detection with ultrasonic devices appears to be a promising technique for use in tank testing. No tracer gas is required and detection is possible some distance away from the leak. The use of ultrasonic frequencies minimizes the possibility of ambient noise masking' small leaks. The primary disadvantage of this method is the lack of visibility of detected leaks. Thus, this device may only be practical for grooming or pretesting the tanks.

3. Acoustic Emission

Acoustic emission testing is widely used to locate weld flaws in steel pressure vessels. In this technique, transducers are attached directly to the vessel. The transducers sense high frequency (100 KHz) stress waves originating from localized flaws. Several transducers are used together with a computer to triangulate to the location of the flaw. This technique has not been widely applied for the detection of leaks. In one set of available test data[18], leaks were detected when the internal pressure reached 3600 psi in a steel vessel. It was reported that at the beginning of the leak the indication was easily recognized, but once the leak was established, the leak indication was not distinguishable from the background noise.

Acoustic emission is not considered to be a viable leak detection technique for ship tanks. The transducers must be attached directly to the tank, so noise originating anywhere on the ship may be detected, and the method is particularly sensitive to grinders and grit ground into steel underfoot. Since a shipyard is not likely to stop all work on a vessel for the duration of a test, successful application of acoustic emission for leak detection on a ship under construction is unlikely.

E. Other Methods

1. Liquid Crystal

Liquid crystals are a relatively nondestructive testing technique. These materials are cholesteric esters which undergo changes in their liquid structure in response to changes in temperature. These materials are usually colorless on either side of the liquid crystal state, but will reflect different colors depending on the temperature of the environment. It is this characteristic that is used to identify material flaws. These flaws may be cracks, or leaks which distort the normal flow of heat sufficiently to disturb the normal temperature pattern of the material being tested. Since irridescent colors of liquid crystals arise from reflected light it is usually advantageous to spray the liquid crystal material on a dark background, like water soluble black paint.

A vessel may be inspected for leakage by coating the outside with a liquid crystal material, and pressurizing it to about 5 psi with a containment gas such as acetone. Any gas escaping through small leaks in welds will cause a change in the transition temperature of the coating, and thus the color, in the vicinity of the leak.

The liquid crystal method is a new and only partially developed technique. Its primary advantage is the visually observed indication. The test procedure is roughly equivalent to that for the chemical reaction systems . Disadvantages of the method are that materials have to be applied to both sides of the barrier being inspected, quantitative results are not provided, the color response is often transitory and the materials are expensive. For these reasons we believe liquid crystal leak detection, in its current state of development, is inferior to leakage testing with the chemical reaction systems.

2. Laser Excited Interferometry

Laser excited interferometry is an active acoustic leak detection system in the early stages of development. The primary application of this method is for the detection of leaks in buried pipelines. This method differs from that of the ultrasonic technique in that the detector senses ground motion rather than acoustic vibrations.

Leak detection with this technique consists of pressurizing the pipe and introducing an acoustic signal in the range of 200-2000 Hz. The motion of the earth's surface over the pipe is monitored with a laser interferometer. This device is a folded Michelson interferometer which has a minimum displacement resolution of 1.64 x 10^{-9} ft(19). When the interferometer is positioned over a pipe the device senses the radial wall displacement produced by internal acoustic pressure variations. When the interferometer is positioned over a leaking pipe the normal signal is distorted. The electronics associated with the interferometer are designed to detect the presence of a distorted signal..

The laser exicted leak detection technique is in the early stages of development. It would appear that practical application of this method for leak detection on ships is some years away.

3. Radioactive

Leak testing of small tanks can be performed using a radioactive gas. The tank is pressurized to a moderate pressure with a radioactive gas in air. Then it is inserted into a larger vessel. After a sufficient period of time, air samples taken from the larger vessel may be checked for radioactive contamination. The counting rate determined by a radiation detector is directly proportional to the amount of gas which has leaked from the test tank. The sensitivity of this method is about 10^{-5} atm-cc/sec. Note that the leak location using this method is not possible. Because of potential personnel hazards and because leaks cannot be located, radioactive leak detection is not considered to be an acceptable tightness testing technique for the shipbuilding industry.

4. Thermography

Thermography or infrared imaging is a relatively new tool for detecting thermal gradients. In this technique, infrared light viewed by the camera is displayed on a television screen. Temperature variations show up as different shades of gray, or in some cases different colors. Thermal imaging cameras have temperature resolutions on the order of 0.2°C(20). Normally, the camera measures temperature gradients within a specified temperature range. It is necessary to calibrate the instrument against a known temperature to ensure accuracy of the readings.

Infrared imaging is currently used in medical research for the detection of cancer, areal surveys for residential heat loss and a wide variety of other applications. However, the technique does not appear to have been applied to the problem of leak location. This may be because until recently, the equipment was both bulky and expensive. Although the cost is still high, as much as $40,000, some new systems, including infrared camera, electronics and a television monitor are now small enough to be carried by a man(21). Other units with less sensitivity (about l°C) and a less sophisticated display cost less than $5000. Thermography appears to have potential for task testing because of the good thermal sensitivity and because detection may occur at a distance.

5. Halide Torch

Leak testing with a halide torch is similar to testing with a halogen detector, only the detector is different. The comments regarding diffusion and stratification of the tracer gas described earlier for halogen detection also apply to this technique. The halide torch consists of a burner connected to a halide free fuel such as alcohol. Some of the air for combustion is drawn into the flame through a flexible tube to the bottom of the flame. When the flexible tube passes near a leak, the halogen tracer laden gas is drawn through the tube and into the flame. The flame is pale blue if only air is burned, the presence of halogen vapors is indicated by a green flame. The sensitivity of this method is about 10^{-4} atm-cc/see, using 100% tracer.

Leak location with the halogen torch is about as sensitive, fast and convenient as testing with soap bubbles. The leak indication is visible as long as the torch remains in the vicinity of the leak. The disadvantage of this method is that no means of accurate calibration is available, and that contamination, perhaps from larger leaks in the vicinity, may mask indications of smaller leaks. In addition, the procedure consumes oxygen and may give off enough toxic fumes to make it unsafe in an unventilated, confined area. For these reasons, the halide torch is not considered to be an acceptable tightness test.

F. Ratings of Methods for Ship Tank Testing

The following discussion is an evaluation of the various leak testing methods described in Section V. The purpose of this evaluation is to determine which methods merit additional testing and analysis. By rating each method according to its potential as a replacement for the standard air or hydrostatic leak detection test, it was determined which methods should undergo further laboratory testing.

1. Productivity

Here, each potential test method is rated in terms of its productivity for tank testing. The true impact of a new test method on ship productivity can only be determined after a period of successful use by the shipyard, so the ratings given each method simply reflect the best judgment of the team of experts based upon current knowledge of the test method and shipyard practice. On the bottom line, improvement in ship productivity is a reduction in production cost. As listed in Section IV.B, factors which affect cost in tank testing and shipbuilding in general include:

- Test time
- Man-hour expenditures

- Training of personnel
- Cost of expendable
- Equipment depreciation costs
- Disruption of schedule
- Anything that adversely affects the work of other trades

A detailed assessment of each factor for each test method was not made, but each factor was considered in the ratings of each method.

For tank testing two different types of tests would be ideal, one test method for use by the shipbuilder to help him produce a tight tank and one to achieve tank approval by the owner, inspector and/or sunveyor. The need for two different test methods is clear from the constraints on new test methods described in Section IV. A test method for tank grooming by the shipyard must emphasize productivity; a method for approval testing must emphasize visibility and acceptance by inspectors and surveyors. For both test methods, an air-based test procedure is proposed so that all tightness testing can be performed prior to launch.

Ranking of the test methods discussed in Section V are given in Table V.8. Ratings extend from 1 to 10 with 1 being the lowest rating and 10 the highest. Methods are rated for suitability in grooming the tank and for approval testing. The range of sensitivity of each method, taken from Section V, is shown for further comparison. Based on the information available from the literature, all "new" methods considered match the sensitivity of air and soap or water.

Both the standard air test and the hydrostatic test are included in the ratings for reference. Notice that the hydrostatic test has been assigned the lowest rating for grooming tanks but the highest rating for approval testing. It rates low for grooming because it is time consuming, disruptive to work by other trades and adversely affects scheduling. It is rated high for approval testing because of its universal acceptance by owners and regulatory agencies. Air and soap rates fairly well in both categories. It rates well in productivity because it is air-based and generally not too disruptive of work by other trades (use of the vacuum box at the block stage gives good schedule flexibility); however, inspection is tedious and time consuming. It was assigned a rating of 6 in approval testing because it is already accepted by owners and regulators for non-critical boundaries.

Generally, the other methods rate well in the approval testing if they provide visibility equal to or greater than a hydrostatic test. Methods rate well in grooming if, in the opinion of the team of experts, they will reduce overall costs relative to the air and soap test. All are air-based and will probably require tank pressurization as in the air and soap test so that gains in productivity are generally based on ease of use and reduced inspection time. Low ratings in productivity were assigned to those methods

TABLE V. 8. RATINGS OF TEST METHODS

Test Type	Sensitivity* (atm-cc/sec)	Tank Grooming	Approval Testing
Hydrostatic	10^{-3} - 10^{-4}	1	10
Air and Soap	10^{-3}	8	6
Chemical Methods:			
Dye Activation	10^{-3}	5	10
Penetrants (incl. U.V.)	10^{-5}	5	7
Tracer Methods (all)	10^{-3} - 10^{-14}	4	1
(Halogen			
Mass Spectrometry			
Light Absorption			
Thermal Conductivity)			
Acoustic:			
Sonic	10^{-2}	1	1
Ultrasonic	10^{-2} - 10^{-4}	10	1
Acoustic Emission	?	1	1
Other:			
Liquid Crystal	?	1	
Laser Excited Interforometry	?	1	1
Radioactive	?	1	1
Thermography	?	6	7
Halide Torch	10^{-4}	5	3

*Refer to Section V for definition of sensitivity.

Note: Highest Rating is 10.
Lowest Rating is 1.

which appear to be unsuitable for tank testing. For example, the radioactivity methods are unsuitable because of the potential hazards involved. Also, low ratings in productivity were given to those methods which are in early stages of development and difficult to access, as is the case with the liquid crystal method.

2. Methods Selected for Laboratory Evaluation

New methods in Table v.8 which ranked highest in the categories of Tank Grooming and Approval Testing warrant further investigation. Four methods rate well. These are

- o Dye activation
- o Penetrants
- o Ultrasonics
- o Thermography

Before proceeding with laboratory tests, the details of implementing these methods for testing ship tanks were studied and the procedures discussed with members of the SNAME SP-II Panel on Outfitting and Production aids. The use of dye activation for testing ship tanks was eliminated from further consideration at this stage in the evaluation process.

There are several reasons why dye activation was discarded. The proposed method would use a trace gas added to the air inside the tank, which, when diffused through leak holes to the tank exterior, would react with a chemical developer on the exterior surface. The reaction would cause a discoloration of the developer wherever through holes were located. This method was chosen for further evaluation, primarily because it offered the possibility of improving leak visibility. Several major drawbacks exist in the implementation of this method for ship tank testing. These are:

- o Some potential trace gases (such as ammnonia) are toxic and could pose a health hazard.
- o Uniform dispersion of the trace gas throughout the test tank would be very difficult in tanks with internal structure (webs, stiffeners, etc.) which are typical of ship ballast tanks.
- o Time, effort, and money for testing would be comparable to, if not greater than, the current air test.
- o It is unlikely that this test would be more sensitive than a hydro test or a standard air and soap test, although visibility could be improved.

The most serious problem is the difficulty of assuring that adequate concentrations of the trace gas are present. in all parts of the ship tank. This would require the use of large circulation fans and concentration probes at several tank locations. Even then, the time to obtain adequate diffusion will probably be long. Thus, this method was not included in the laboratory evaluations.

VI. EVALUATIONS OF SELECTED LEAK DETECTION METHODS

Laboratory tests were conducted to evaluate the feasibility of the detection methods which rated high in the preliminary evaluations given in Section V. These methods are:

- o Dye activation
- 0 Ultrasonics
- 0 Thermography

The lab tests generated data in three areas for each method. These areas were:

- o The sensitivity of leak detection as a function of liquid head or tank pressure
- 0 The visible range for leak detection
- 0 The minimum detectable flaw size or maximum undetected leak rate.

Tests on these methods were performed with the stainless steel orifices used in the evaluations of the water and air tests (see Section 11.C.3). Results of the laboratory evaluations are presented in the following paragraphs.

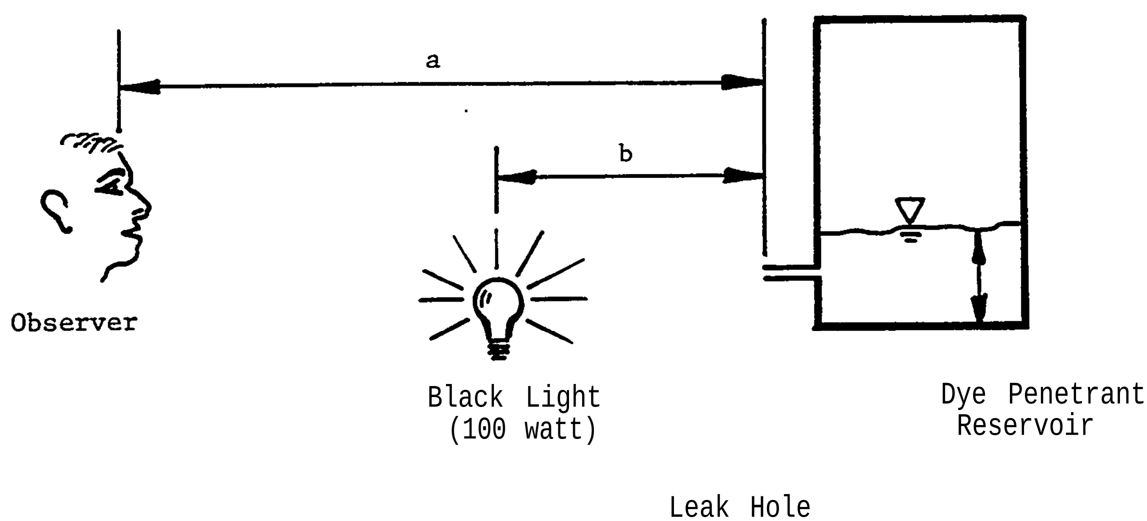
A. Dye Penetrants

Two dye penetrants used for the detection of through flaws were tested for potential use in tank tightness testing. The penetrants were Magnaflux Red ZL-3A Zyglo Penetrant and Sherwin LAB-L719. Both penetrants were fluorescent liquids that became brightly illuminated when exposed to ultraviolet light.

The previously described stainless steel capillary tubes were used as test flaws. The test penetrant was allowed to flow through the capillary tube and its detectability evaluated. The basic procedure was to place the test capillary in a dark room, illuminate the flaw with a black (ultraviolet) light, and observe the hole's detectability using the naked eye. The schematic on Figure VI.1 depicts the test setup.

Each capillary with a hole diameter less than 0.0061 inch required overpressurizing to force the penetrant through the entire length of tube. The required pressure levels for these cases are presented in Table VI.1. Capillary action was sufficient to draw the penetrant through the holes 0.0061 inch or greater in diameter. As evidenced by the data in Table VI.1, the surface tension characteristics of the penetrants were superior to those of water. Less overpressure was required to force penetrant through a given hole size than was required for water.

Lab tests for visibility are summarized in Table VI.2. The test data demonstrate the differences in the visibility of the two test penetrants. The Sherwin penetrant had superior visibility. Also, the amount of light incident



a = maximum distance from the hole at which the hole is visible to the naked eye

FIGURE VI.1. DYE PENETRANT LEAK DETECTION EVALUATION SETUP

TABLE VI. 1

MINIMUM DETECTABLE HOLE SIZES FOR VARIOUS PRESSURE DROPS ALONG THE LENGTH OF A STAINLESS STEEL CAPILLARY TUBE*

Hole Diameter (inch)	Minimum Pressure Drop Along Length of the Tube (psig)	
	Magnaflux Red ZL-3A	Sherwin LAB-L719
0.0042	1.0	2.0
0.0036	3.0	3.0
0.0027	5.0	7.0
0.0021		
0.0019		
0.0018		
.0.001.6	25.0	30.0

Tube length is 0.375 in.

TABLE VI.2

LEAK VISIBILITY DISTANCES USING MAGNAFLUX AND SHERWIN DYE PENETRANTS

Hole Diameter (inches)	a^* (feet)		h^* (feet)
	Magnaflux	Sherwin	
0.0338	25.0	25.0	1.0
0.0338	25.0	25.0	5.0
0.0142	25.0	25.0	1.0
0.0142	15.0	25.0	5.0
0.0103	25.0	25.0	1.0
0.0103	15.0	25.0	5.0
0.0073	25.0	25.0	1.0
0.0073	8.0	15.0	5.0
0.0061	5.0	25.0	1.0
0.0061	1.5	10.0	5.0
0.0042	5.0	25.0	1.0
0.0042	1.5	10.0	5.0
0.0036	5.0	25.0	1.0
0.0036	1.5	10.0	5.0
0.0027	5.0	25.0	1.0
0.0027	1.5	8.0	5.0
0.0016	5.0	25.0	1.0
0.0016	1.5	8.0	5.0

*See Figure VI.1 for definition.

on the leak area significantly affected detectability. For example, the Sherwin penetrant detected a 0.0016 inch diameter hole at a viewing distance of 25 feet when a 100 watt ultraviolet light was placed one foot from the hole. For the same test conditions, but with the ultraviolet light placed 5 feet from the hole, the hole was visible only from distances of 8 feet or less. If this detection method was used onboard a ship, the effectiveness of the test would be significantly influenced by the amount of ultraviolet light incident on the test surface.

The laboratory tests found the accuracy of a tightness test using a dye penetrant to be comparable to a hydrostatic or air and soap test (meaning the minimum detectable hole size is approximately the same). In evaluating the cost of performing a penetrant test, the entire process was analyzed. Time would be required to (1) apply the penetrant to the test surface, (2) set up proper lighting of the surface, (3) check for leaks, and (4) remove the penetrant after testing is complete., The time necessary to complete steps (l), (3), and (4) is estimated to be about the same as for standard air test. The lighting might require some additional time. An additional cost would be incurred in the purchase of penetrant (and, in some cases, penetrant remover). The current cost for penetrant is about $10 per gallon. Plus, for this application, the penetrant would not be reusable.

Members of the SNAME SP-11 Panel on Outfitting and Production Aids were consulted to obtain their opinions on the practicality of this method. Most indicated that this technique does not yield any substantial savings in time or money over the current methods. As a result, the dye penetrant method was dropped from consideration as a potential replacement to the standard air or hydro test.

B. Ultrasonics

An ultrasonic detection method has been used successfully in the past by at least one shipbuilder (Newport News Shipbuilding and Dry Dock Co.) for purposes of locating relatively large leaks in ship tanks. The basic concept is to generate ultrasonic noise (in the frequency range of 36 to 44 kHz) at a leak opening and then use an ultrasonic detector to locate the leak. There are several ways of creating the ultrasonic noise. Two of the most practical methods are:

- Blow air through the leak hole to create air turbulence (with a frequency of about 40 kHz) at the hole exit.
- Use a sound generator to produce sound waves (in the 36 to 44 kHz range) that will pass through the hole.

During the laboratory evaluation, both of these techniques were examined.

The ultrasonic detector used for the laboratory study was chosen after a survey of commercially available detectors was completed. It was found that most of the commercial detectors were similar in capabilities and performance. The current price range of the detectors is about $300 to $1,500. The test model chosen for use in the laboratory study was a Hewlett-Packard Ultrasonic Translator Detector (Model 4918). Its cost and performance were typical. of currently available units.

The test procedure was to either (1) blow air through the stainless steel capillary tube in order to create air turbulence at the leak exit or (2) send an ultrasonic noise signal (on the order of 40 kHz) through the capillary and then use the ultrasonic detector to identify the leak by sensing the noise. The schematic shown on Figure VI.2 depicts the basic test setup.

The test results for the air-based ultrasonic method are presented in Table VI.3. Comparing these results to those for the standard air and soap test, it was found that the ultrasonic method was slightly less sensitive. For example, with an air pressure drop along the length of the tube of 2 psig, the air and soap technique detected holes as small as 0.002 inch in diameter. A hole this size was detectable from a distance of 3 to 5 feet. For the same pressure, the ultrasonic method could only detect holes 0.0073 inch in diameter or greater. However, the holes were detected from distances of 15 feet or greater. The reason smaller diameter holes were not detected with the ultrasonic method was that the flow rate of air through the holes was not sufficient to create measurable turbulence at the hole exit.

The ultrasonic tests conducted with a noise generator are summarized in Table VI.4. The minimum detectable hole size was 0.0073 inch in diameter at a distance of four feet. It was found that the sound emitted from the hole was very directional. The detector had to be placed almost in line with the direction that the tube was pointing before any measurable signal was observed. This problem could severely limit the effectiveness of this technique for circuitous flaws in a ship tank.

Overall, the air-based ultrasonic test was superior to the noise generator method. Both methods had about the same sensitivity (0.0073 inch diameter hole was the minimum detectable hole size) but neither was as sensitive as an air and soap test although the difference was slight.

An ultrasonic test would probably be easier and quicker to administer than a hydro or air and soap test. The sensitivity of the ultrasonic method would be almost as good as the current tests. However, some potential problems with the ultrasonic method do exist. First, lab tests indicated extraneous noises in the 36 to 44 kHz range could significantly affect test sensitivity. For example, noises from hand drills, shoes sliding across a concrete floor, tools rattling in a tool box, a person sneezing all interfered with the leak signal being measured by the ultrasonic detector. This could be a serious problem onboard a ship under construction since many extraneous noises would probably be present during the tank testing.

Another potential problem with ultrasonic testing is reflection of acoustic signals. On some occasions, noise signals bounce off one or more surfaces creating reflected signals. Smooth, flat metallic surfaces, such as ship tank walls and internals might possibly reflect signals. These reflected signals could cause erroneous indications of leak hole locations. However, the lab tests indicated that reflected signals would not be a significant problem if the leak holes were small (i.e., pinhole-type leaks in welds) because the noise level created at small holes is relatively low and is attenuated quickly. Also, Newport News representatives did not report any acoustic reflection problems during their test work. This problem is mentioned only to indicate that the potential exists for acoustic reflection to occur, but preliminary data indicate it is probably not important.

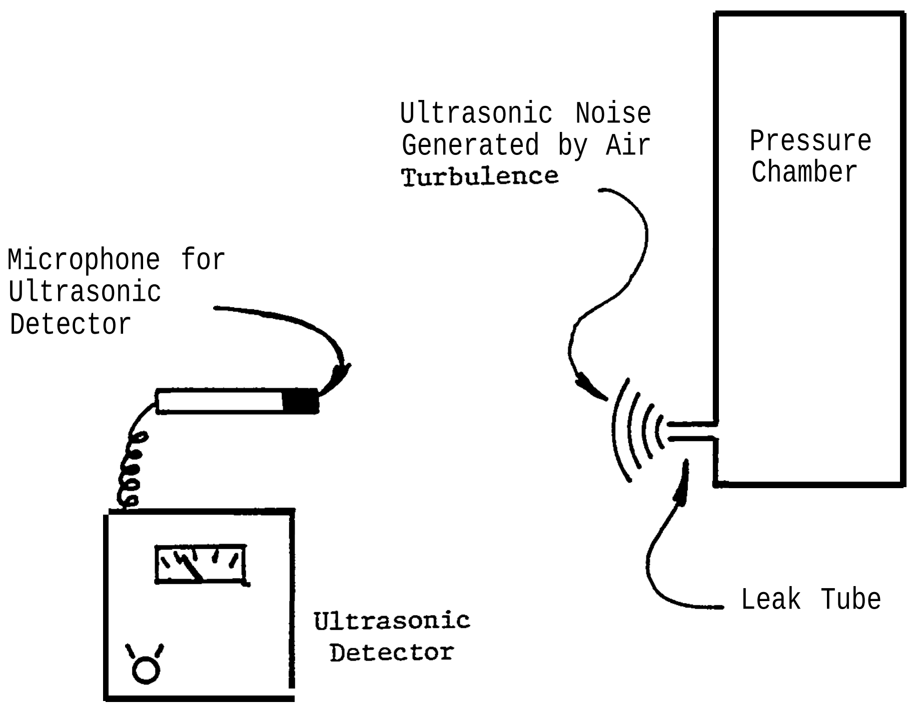


FIGURE VI.2. AIR-BASED ULTRASONIC DETECTION TEST SETUP

TABLE VI. 3

AIR-BASED ULTRASONIC LEAK DETECTION SENSITIVITY RESULTS

Minimum Pressure Drop Along Length of the Tube (psig)	Maximum Distance From Leak At Which Detection Is Possible (ft)					
	Hole Diameter (in.)					
	0.0042	0.0061	0.0073	0.0103	0.0142	0.0338
1.0	ND	ND	ND	ND	1	20
2.0	N-D	ND	15	15	25	> 30
4.0	ND	ND	15	20	30	>30
6.0	ND	15	25	30	>30	>30
8.0	ND	15	25	>30	> 30	>30
10.0	ND	25	30	>30	> 30	>30

ND= Not Detectable

TABLE VI. 4

*NOISE GENERATOR-BASED ULTRASONIC
LEAK DETECTION SENSITIVITY RESULTS

Hole Diameter (in.)	Maximum Distance From Leak At Which Detection is Possible (ft)
0.0061	ND
0.0073	4
0.0103	8
0.0142	10
0.0338	10

ND= Not Detectable

*Soncaster Noise Generator Used for All Tests

It was concluded that ultrasonic testing would be a relatively inexpensive and quick method for tightness testing; But the sensitivity-of an ultrasonic test would be slightly inferior to current test methods. Also , extraneous noises could severely limit the effectiveness of the test. In addition, leak hole locations would be detected audibly, rather than visibly, which some inspectors find objectionable.

Because sensitivity of ultrasonic devices is not equal to water or to air and soap, regulators-and shipbuilders may not accept ultrasonic testers as a replacement for current methods. However, as shown in Section VII, ultrasonics can readily detect flaw sizes which are easily sealed by coatings. If coatings are accepted by regulators, ship owners, and shipbuilders as suitable means of sealing small flaws (less than 10 mil characteristic dimension), then ultrasonics can be considered as a very viable test method for ship tanks.

C. Thermography

Thermographic leak detection in which leak holes are detected using an infrared sensing device has been successfully performed at Newport News Shipbuilding and Dry Dock Company. The tests were performed on membrane tanks designed for transporting liquid natural gas. Double wall construction of the tanks was particularly adaptable to this method of leak detection because only a small volume, between the tank walls, had to be filled with a chilled fluid. Leaks were detected by looking for temperature differences (cool spots) where leaks occurred. The chilled fluid was nitrogen gas with an initial temperature of 50°C cooler than the tank wall. Thermographic detection worked well for this application, and so it was decided that a laboratory study at SWRI was appropriate. The thermograph used for testing was available at SWRI. It was built by Dynalab, Inc., and had a calibrated sensitivity of O.l°F on a solid surface at a distance of 3 feet. This scanner was typical of currently available hardware. The present cost of a new infrared scanner is approximately $40,000.

The lab procedure was based on the assumption that an initial differential of 1.5°F between the tank air temperature and the tank wall temperature could be obtained relatively easily in a large ship tank. In the laboratory test, air was blown through a test leak, a pinhole weld flaw in a l/4-inch thick butt weld. The hole size was estimated at about 0.05 inch in diameter. The initial temperature differential between the air and the weld surface was 1.5°F, with the air being colder than the welded plate. The air was blown through the test hole for 15 minutes before the hole was examined with the thermograph. At the end of 15 minutes, the hole was examined with the infrared scanner located 5 feet from the test surface. No detectable temperature gradients at the hole were observed, so the scanner was moved to within 6 inches of the test surface. Again, no gradients were measured. The test was then repeated with the air pressure drop increased to 10 psig to increase the flow rate of cool air through the hole. As before, no temperature gradients at the hole were observed.

These test results indicated the thermographic technique would be ineffective for most test situations. The test pinhole leak (about 0.05 inch in diameter) was considerably larger than the minimum size that could be detected by a hydrostatic or air and soap test. Yet, the thermograph was unable to detect the leak because no detectable temperature gradients were produced in the steel plate. The metal temperature at the leak hole remained at about the same temperature as the surrounding structure (about 1.5°F warmer than the air passing through the hole). Increasing the temperature difference between the air and the tank wall might improve the probability of leak detection by producing a temperature gradient greater than 0.1°F at the leak. However, this temperature differential would probably have to be substantial (greater than 10°F) and might be difficult if not impossible to achieve and maintain for any length of time in a large volume tank. Consequently, the thermographic detection method would not be a viable technique except for applications (such as liquid natural gas carriers) where special tank construction would be adaptable to this method. Thermography is not recommended for general use as a tightness test.

VII. EVALUATION OF PRIMERS AND COATINGS FOR LEAK SEALING

A. Testing Procedure

Current testing regulations require tank tightness testing to be performed before the tank walls are primed or coated. A laboratory investigation examined the effects of primers and coatings on standard air and water tightness tests. The research departments of the three major marine paint manufacturers were contacted concerning currently available products. These companies were Devoe and Raynolds Company (Marine Division), Carboline International, and Hempel's Marine Paints, Inc. In addition, guidance was obtained from some shipbuilding industry representatives on typical application procedures and coating thickness.

Each paint company furnished samples of currently available primers and coatings. Table VII.1 presents a complete listing of the samples used during the laboratory testing. The majority of the paints were inorganic zinc primers or epoxy coatings. These were considered state-of-the-art products.

A group of weld flaws containing pinhole-type leaks were fabricated for testing. The weld flaws were contained in 1/4 inch fillet welds connecting two 1/4 inch thick steel plates (see Figure 11.7). Other test flaws, consisting of round holes ranging from 0.040 to 0.161 inch in diameter, were drilled through 1/4 inch steel plates. The laboratory investigators examined how the weld flaws and drilled holes were affected by paint coatings.

Leaks were located and marked on the weldments during the air (with soap) and water tests described in Section 11.C.3.C. The specimens were then painted (on one surface only) according to the manufacturer's specifications and retested. The weld specimens and two round hole specimens were painted with a brush, while a third round hole specimen was painted with a spray gun. As for the tests without coatings, the coated specimens were tested for flaws at pressure levels up to 50 psig. Each pressure level was held for 10 minutes. The painted side of the test specimen was the low pressure side.

B. Test Results

Test results are summarized in Appendix E. It is obvious from the test data that the coatings were very effective in plugging leaks in the welds. Many relatively large flaws creating-profuse bubbles in the air test and squirts in the water test were sealed by the coatings. It appeared that all of the coatings tested worked equally well at plugging the small holes. All but eleven of the weld flaws were sealed by the coatings at pressures up to the maximum test pressure of 50 psig. Ten of these eleven flaws which leaked after coating were detected with air at 1.0 psig prior to coating. The other flaw was detected by air at 2.0 psig. Consequently, it is difficult to determine the size of these flaws. More definitive results on the hole size which can be sealed by coatings were obtained from the tests on drilled holes.

TAB`LE VII .1

TEST PRIMERS AND COATINGS

SUPPLIER*	PAINT NAME	PAINT TYPE
	Hempadur 1540.	Epoxy-amine finish
DR	Devran 20247	Polyamide epoxy primer
DR	Devran 21556	Polyamide epoxy finish
DR	Devran Anti-Corrosive 23004	Polyamide epoxy finish
DR	Devran 24471 HS	Ketimine epoxy finish
DR	Catha-Coat 302	Inorganic zinc primer
CI	Carbo Zinc 11	Inorganic zinc primer
CI	Carbomastic 15	Aluminum epoxy mastic
CI	Carboline 187 HFP	Epoxy-amine primer and finish
CI	Carboline 191 HB	Polyamide epoxy primer and finish
CI	Phenoline 373	Modified phenolic primer and finish

*Supplier codes:

H - Hempel's Marine Paints, Inc.
'DR - Devoe and Raynolds Company (Marine Division)
CI - Carboline International

TABLE .2

LEAK DETECTION RESULTS ON TEST HOLES* BRUSH COATED WITH DEVOE AND RAYNOLDS HS TANK PRIMER AND COATING 24471**

Hole Diameter [inches)	Pressure Level*** for Leak Detection (psig)
0.0400	ND
0.0420	ND
0.0465	ND
0.0550	ND
0.0635	ND
0.0700	ND
0.0760	ND
0.0810	ND
0.0860	ND
0.0935	ND
0.0980	ND
0.1015	ND
0.1065	ND
0.1110	30.0
0.1285	ND
0.1405	ND
0.1470	ND
0.1520	5.0
0.1570	ND
0.1610	ND

* Test holes drilled in l/4-inch steel plate
** Coating applied with a brush
*** Maximum pressure level of 150 psig

ND - Not detected

TABLE VII.3

LEAK DETECTION RESULTS ON TEST HOLES* BRUSH COATED WITH CARBOLINE INTERNATIONAL'S PHENOLINE 373 PRIMER AND COATING**

Hole Diameter (inches)	Pressure Level*** for Leak Detection (psig)
0.0400	ND
0.0420	ND
0.0465	ND
0.0550	ND
0.0635	ND
0.0700	ND
0.0760	ND
0.0810	ND
0.0860	ND
0.0935	ND
0.0980	ND
0.1015	ND
0.1065	ND
0.1110	ND
0.1285	ND
0.1405	ND
0.1470	ND
0.1520	ND
0.1570	ND
0.1610	ND

* Test holes drilled in l/4-inch steel plate

** Coating applied with a brush

*** Maximum pressure level of 150 psig

ND - Not detected

TABLE VII .4

LEAK DETECTION RESULTS ON TEST HOLES SPRAY COATED WITH CARBOLINE INTERNATIONAL'S PHENOLINE 373 PRIMER AND COATING**

Hole Diameter (inches)	Pressure Level*** for Leak Detection (psig)
0.0400	ND
0.0420	ND
0.0465	ND
0.0550	ND
0.0635	ND
0.0700	ND
0.0760	HNP
0.0810	HNP
0.0860	HNP
0.0935	HNP
0.0980	HNP
0.1015	HNP
0.1065	HNP
0.1110	HNP
0.1285	HNP
0.1405	HNP
0.1470	HNP
0.1520	HNP
0.1570	HNP
0.1610	HNP

* Test holes drilled in l/4-inch steel plate

** Coating applied with a spray gun.

*** Maximum pressure level of 150 psig

ND- Not detected

HNP- Hole not plugged by test coating, i.e., a paint film did not form over the hole during spraying.

The hole sizes in the round hole specimens are given in Table VII.2. Of the three round hole specimens, one was brush painted with Devoe and . Raynold's Devran 24481 HS Tank Primer and Coating (a relatively thick viscous paint), another was brush painted with Carboline International's Phenoline 373 Primer and Coating (a less viscous paint), and the third was spray painted with Phenoline 373. All were coated on only one surface. On the two brush painted specimens, all holes (up to 0.161 inch in diameter) were covered with a paint film during the coating process. On the spray painted specimen, holes between 0.040 and 0.070 inch in diameter were covered by the paint. The coating thickness on each of the three specimens was approximately 0.030 inch.

Each specimen was tested for pressure levels up to 150 psig. None of the plugged holes were opened in the-two specimens painted with Phenoline 373. Only two were opened in the Devran 24471 HS specimen. The results for the three specimens are presented in Tables VII.2 through VII.4. During the tests, each pressure level was sustained for ten minutes. The pressure levels were 1, 2, 5, 10, 20, 30, 40, 50, 75, 100, and 150 psig. The 50 psig level was held constant for a 24-hour period with no apparent change in the test results. Each specimen was tested with the coated surface on, first, the low pressure and then, the high pressure side. The results were identical for both cases.

In addition to the static pressure tests mentioned above, some pressure cycling tests were conducted on the round hole specimens. Each was cycled 50 times from zero to 50 psig. During these tests, no additional leaks developed in the plugged holes on any of the specimens.

The results of the tests on the round hole specimens demonstrated that small holes can be plugged by coatings at pressures well above hydrostatic pressures that occur in integral ship tanks. If the coatings are not erroded away or weakened over a period of years then the seal may be permanent; however, there is also an uncertainty about the effect of ship hull stresses produced by the hydrostatic loads and the "working" of the ship at sea. The possibility exists that loads of this nature could cause (1) a coating to break apart or detach from the wall surface or (2) a flaw to enlarge or expand. Either of these problems could allow leaks to develop after a period time. It seems unlikely that ship stresses across small flaws, e.g., with a characteristic dimension of 10 roils or less, would be sufficient to fail the coating, but the effect of these loads must be investigated before coatings can be regarded as permanent seals for small flaws.

VIII . A STATISTICAL APPROACH TO TANK TESTING

A. Current Test Methodology

Current tank testing methods are reviewed and discussed in Section II. Many different methods are used and the application of each method varies from shipyard to shipyard and also by the ship type. In general, though, two basic tests are used, the air test and the hydrostatic test, and current testing procedures are as follows:

> First, air tests, with a soapy solution as the leak detector, are performed for all (or almost all) tanks to check for tightness. These tests are normally performed before launch and may or may not be witnessed by inspectors and/or sumeyors, depending upon whether or not approval is sought. Second, hydrostatic tests are performed after launch for a selected group of tanks in order to thoroughly check tightness and to achieve approval.

Since time (and thus, money) is involved in both the air and the hydrostatic tests, a statistical method is sought that would achieve a reduction in cost and amount of testing, eliminate the use of discretion by the inspector in choosing tanks to inspect, and guarantee the same level of assurance as current test procedures. Note that current test procedures refer to the test methodology and not the type of test selected.

A review of shipyards indicates that no standard statistical methodology is available or practiced. However, there are some scattered techniques that are utilized by different shipbuilders or agencies which could form the basis of's statistical method. TWO examples are summarized below:

A Japanese Shipbuilder - A criterion to determine the success or failure of a tank test is based on a system developed by Nippon Kaiji Kyokai. In this system four negative points are assigned for each leak in the water test and two negative points are assigned for each leak in the air test. Also, ten negative points are given for each leak from the crack on a welded joint. If a tank receives more than twenty negative points it must be retested. All leaks found are repaired. This criterion is based upon leakage only. We presume that other criteria apply to structural failures.

U.S. Navy - Surface Ships - All integral tanks are subjected to a completion test. This is an air drop test and, for tanks designated as oil tight or water tight, the allowable pressure drop from a 2.0 psig initial pressure is zero. Tightness tests (hydrostatic tests) are then conducted for selected tanks on a sampling basis. The spaces to be tested will be selected by the Supervisor. At least ten percent but not less than one of each type of tank are tested. Type is interpreted to mean either contents (fresh water, fuel oil, lube oil, reserve feed, etc) or geometry (deep tank, inner bottom, cofferdam, etc.). If any tank fails the hydrostatic test (shows evidence of leakage), it is repaired and retested, and the tanks immediately adjacent to the repaired test are also tested. If there are no adjacent tanks then a tank, similar in construction, but in another location, is tested.

At present the Navy approach is the closest to a true rigid statistical technique. The Navy completion test is similar to the air testing used for "grooming" the tanks in most of the shipyards. The Navy tightness test is now a hydrostatic test; in shipyards this may be called a structural test depending upon its purpose. However, any type of "approval tests" could be used. For tightness only, it may be a new air-based test which is acceptable to owners, regulatory agencies and classification societies. For structural and/or tightness testing it might be a hydrostatic test. Modifying the Navy approach or developing a new sampling criteria for reducing the amount of testing would apply primarily to the approval tests; the more approval tests, the higher the cost to the shipbuilder.

B. Proposed Approach

1. Problems in Current Procedure

There are two basic flaws with the current tank testing methodology. First, no records are kept on tests so that little is known of the past history of tank defects found in testing for any particular shipyard. Secondly, exact procedures and criteria in making approval tests are non-existent, and the inspector or surveyor alone* chooses the tank types to be tested, the type of testing to be conducted, and the criteria for acceptability. The result is widely varying inspection procedures and differing assurance levels on tank integrity and tightness. To correct this situation, it has been suggested that statistical methodology be incorporated into tank approval testing.

2. Data Collection System

Developing a uniform and acceptable data collection system is an essential element in the evaluation of tank testing. With good historical data and records for each shipyard, it will be possible to determine the quality of each tank type built and the reliability of the shipyard. Ultimately, this may lead to the elimination of approval testing in shipyards with an excellent history of quality control.

Major data to be collected would include:

- Tank type - grouped by geometry, contents, or structural components, e.g., bulkhead, tank bottom, or tank top.
- Weld type the weld would be where a flaw occurred, e.g., what type of weld resulted in leakage.
- Number of leaks - how many leaks were repaired as a result of the final inspection.

Other data items would be the shipyard name, ship designation, tank identification number, inspector, date of inspection, tank test type, and noted flaws.

*within the guidelines specified by the regulatory agencies.

Although most tightness testing is related to anks, there are valid reasons for grouping and testing by tank components. The major reason for such grouping is that different testing criteria should be set for different components in a tank. For example, allowable leakage rates should be much higher for bulkheads which contain sluice valves than for bulkheads which do not. Also, bulkheads which separate machinery space from cargo spaces should have a tighter leakage criteria than bulkheads which separate adjacent ballast tanks. The data collection system and the testing procedure would be the same, in principle, regardless of the type of grouping used. Table VIII.1 contains a typical data collection form that could be utilized in such recordkeeping.

Data will be collected by the inspector or surveyor when they make the approval tests. There is also the possibility that the shipyards can monitor their own data, but then their actions and records would need to be subjected to periodic audits by regulatory agencies, ship buyers, etc., to ensure their accuracy. The data will be collected using forms similar to that given in Table VIII.1 and subsequently mailed to a central agency for processing.

The data records will be scanned and summarized in order to establish the reliability of the shipyard in building tanks. One method of summarizing the data would be to simply add up the number of flaws for each tank tested and then calculate the number of flaws per tank. Multiply this rate by the measure of consequence per flaw (e.g., average repair cost per flaw, average index of hazard per flaw), and one could obtain a numerical measure of shipyard reliability. For example, the end number could be the average cost to repair a tank or a measure of the danger associated with leakage in the new tank.

A suggested criterion is to use the NKK bad mark system. Suppose that a tank is assigned two points for each detectable leak and ten points if that leak is from a crack on a welded joint. The total negative points could be determined per tank and an average defect number could be calculated for each tank type built by a particular shipyard.

The history of flaws or leaks in a specific tank type thus will be determined by looking at the tank testing records for many ships. By comparing the calculated numbers with past measures on the shipyard, it would be possible to determine the degree of improvement in tank construction achieved by that shipyard. The data records also would have many secondary uses. For example, it would be possible to compare the work of different shipyards, as well as different inspectors. Tightness measures for specified tank types could be established, and common flaws for specific tanks could be noted and recorded for the participating shipbuilders.

3. Sampling System

Given that an efficient data collection system has been established, the second problem in tank testing is selecting which tank types are to be tested and how many of them to test. At present there may be a tendency by inspectors to choose the tanks the shipbuilder suggests for inspection or to examine every tank being constructed. While it is believed that these inspectors consider the purpose of the tank and the past record of the shipbuilder in testing, there are no established guidelines or procedures in such selections. The decision is left to the discretion of the inspector.

TABLE VIII.1. DATA FORM FOR TANK TESTING

Shipyard: ______________________		
Ship Designation: ______________________		Tank I.D. ______________________
Inspector: ______________	Date: ______________	Test Method: __________

Flaws			
Number	Location	Weld Type	Leak Size
			(Optional)

a. <u>Rationale</u>

One of the objectives of the current program has been to remove this inspector bias by describing statistical sampling techniques that would be applicable in tank approval testing. Use of statistics would make the ABS rules more definitive since each shipbuilder would know the exact procedure to be used in approval testing and the exact criteria for tank acceptance. Ultimately, by testing only a few tanks a high assurance will be obtained that a group of tanks built by a shipyard will be acceptable. Statistical techniques are capable of providing such confidence. The concept is a simple one. By selecting and inspecting a few tanks known to be representative of the whole group of tanks, the inspector can with high confidence state whether the entire group will meet the acceptance standards. Further, by selecting tanks in a random sequence, the inspector removes all bias whether it be personal or induced by the shipyard.

While no standard statistical methodology is currently advocated in approval testing, there are some scattered techniques that are utilized by different builders. For example, the U. S. Navy uses a modified "1O percent sampling rule" in that at least 10 percent but not less than one of each tank type is tested. If no defective are found in the sample, the tanks are accepted. Unfortunately the assurance levels under this sampling plan and similar related ones are unspecified and, in fact, vary according to the number of tanks available for inspection. Other "rule-of-thumb" sampling plans have also proven inadequate due to their inability to specify the sampling risks.

b. <u>Acceptance Sampling</u>

It has been a major objective of the current program to overcome these problems by developing a tank testing sampling plan that has known assurance levels associated with it. It will be shown below that this can be achieved by using the <u>acceptance sampling</u> technique of quality control. In this process a portion of the tanks available for testing are evaluated for the purpose of accepting or rejecting the entire group or lot of tanks as either conforming or not conforming to a quality specification (e.g., number of detected leaks). Further, the procedure prescribes a specified risk of accepting tanks of a given quality. Acceptance sampling does not control quality nor does it estimate the quality of the tank; its purpose is to provide quality assurance by grading a group of tanks as defective or non-defective. It indirectly improves quality through its encouragement of good quality by a high rate of acceptance and its discouragement of poor quality by a high rate of rejection.

Acceptance sampling is not 100% assurance. It involves the risk that the sampled tanks will not reflect the true conditions of the unsampled tanks. Also, it is possible that the tank inspector will not find all the defects in the tanks. Hence, two types of errors can occur:

1) Good tanks can be rejected (this is termed the producer's risk).

2) Bad tanks can be accepted (this is termed the consumer's risk).

Quantifying these risks for a given sampling plan is essential in order to determine the assurance level associated with it. Typically this is achieved in acceptance sampling through the use of an operating characteristic (OC) curve which is a graph of the percent of tanks defective versus the probability that the sampling plan will accept a group of tanks having a specified fraction defective.* The OC curve can be developed by determining the probability of acceptance for several values of incoming quality using for a distribution either the hypergeometric, binomial, or Poisson. The curve does not actually predict the quality of the tanks but merely the probability of accepting tanks which are at any given fraction defective before inspection.

Figure VIII.1 illustrates an ideal OC cume. In this example all groups of tanks with 3% defective or less would be accepted, while those with more than 3% defective will be rejected. The probability of accepting a good group of tanks is 1.0, while the probability of accepting a bad group is 0. Unfortunately, no sampling plan can discriminate perfectly as in Figure VIII.1 and the best that can be achieved is to make the acceptance of good tanks more likely than the acceptance of bad tanks.

Figure VIII.2 illustrates an actual OC curve. Note the difference from the curve in Figure VIII.1. Groups of tanks with 3% or less defective would have a probability greater than 0.5 of being accepted, while those with more than 3% defective would have a probability less than 0.5 of being accepted.

OC curves are affected by the number of tanks available for testing, the sample size chosen, and the acceptance number or number of allowable defective. While these curves can be manually determined, published tables are available for choosing the appropriate sampling plan and the corresponding OC curve. The most common plan is based on attribute sampling. A sample of tanks is chosen and each is classified as good or bad. The number defective is compared with an allowable number stated in the plan and a decision is made to accept or reject the entire group of tanks.

Acceptance sampling may involve single, double, or multiple sampling. In single sampling, which is proposed for use in tank testing, the decision to reject a group of tanks is based on the results of a single sample and the plan consists of a sample size, n, and an acceptance number, C. If the sample has a total number of defects that is greater than or equal to C, the lot is rejected. A schematic operation of single sampling is illustrated in Figure VIII.3.

The acceptance sampling plans are usually categorized in terms of one of several indices. Two familiar ones are described below:

1) Acceptable quality level (AQL) - This is defined as the worst quality level that is still considered satisfactory. The probability of acceptance (P) for a given AQL should be high so that the risk of rejection (l-P), termed the producer's risk, is low.

2) Lot Tolerance Percent Defective (LTPD) - This is defined as unsatisfactory quality or the rejectable quality level (RQL). The probability of acceptance for a given LTPD should be low so that the risk, termed the consumer's risk, that a bad lot is accepted, is low.

*Much of the following discussion is taken from Reference 22.

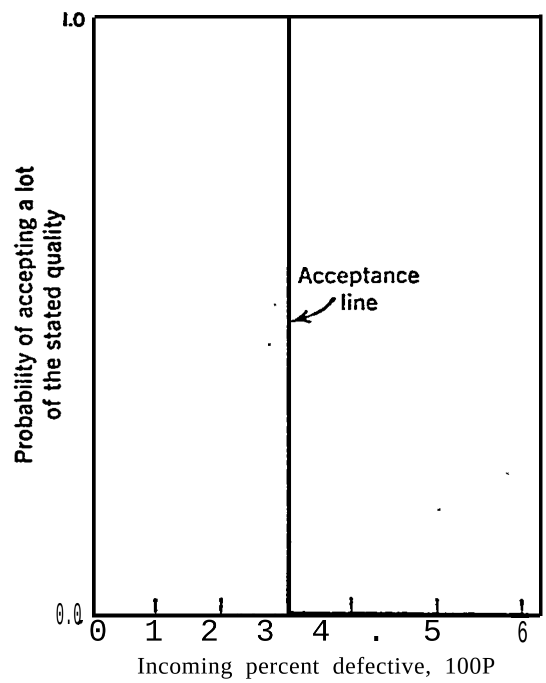


FIGURE VIII.1. AN IDEAL OC CURVE

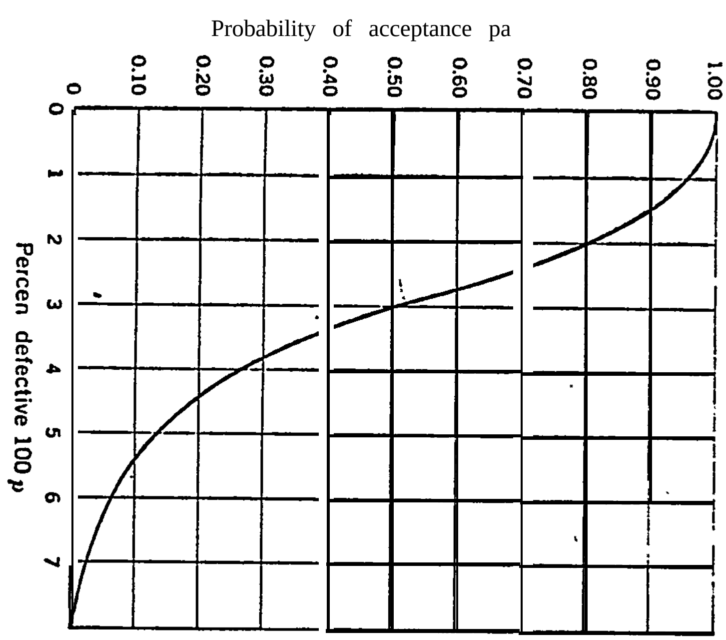


FIGURE VIII.2. AN ACTUAL OC CURVE

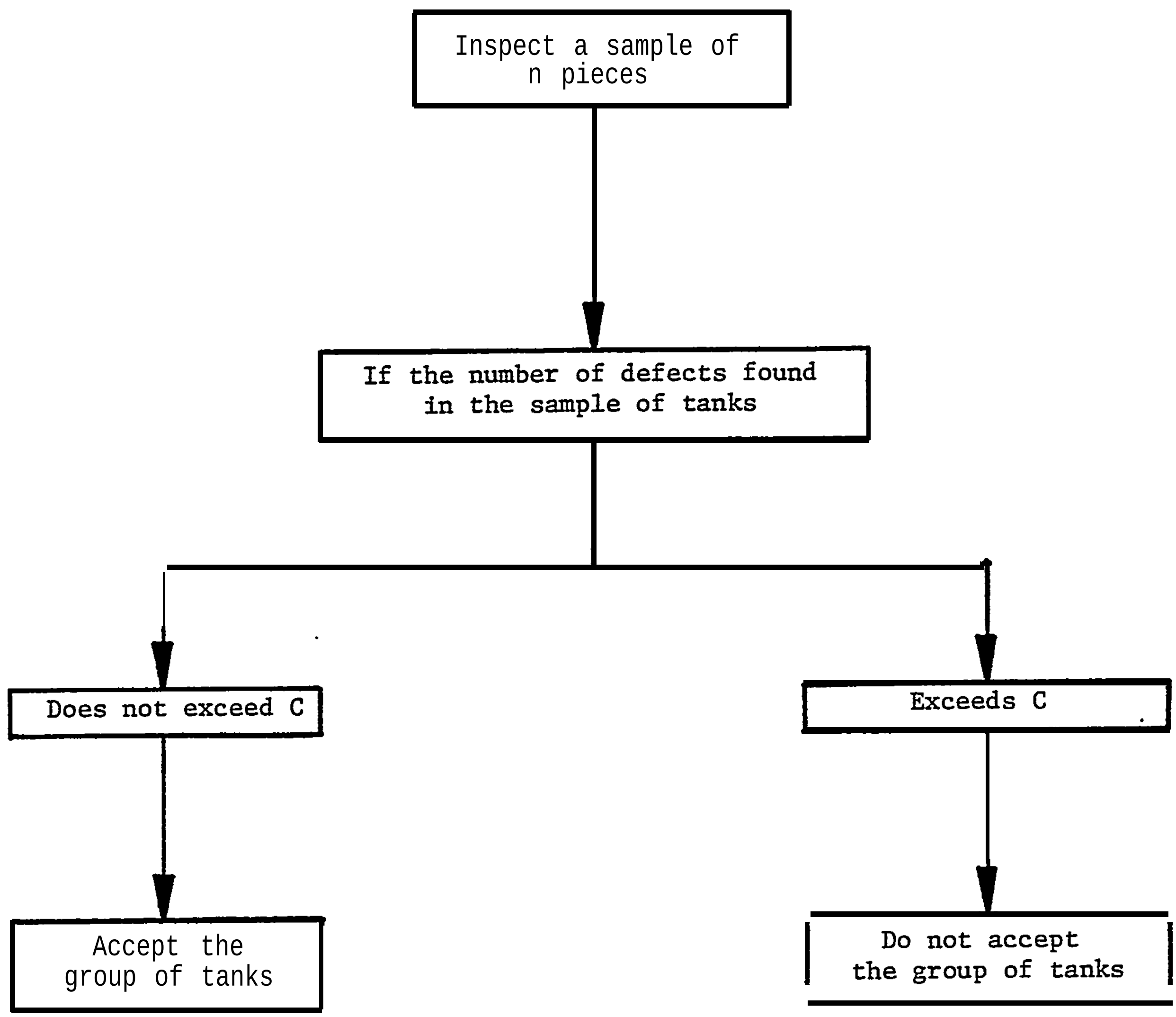


FIGURE VIII.3. SINGLE SAMPLING INSPECTION PROCEDURE

C. Sampling Tables

Published tables are available for determining acceptance sampling plans. The most commonly used ones are the MIL-STD-105D tables (Reference 23), which emphasize the protection of the producer against rejecting good lots. Hence, its quality index is the AQL rather than the LTPD. Applied to tank testing, the purpose of the sampling procedures of MIL-STD-105D would be to so constrain the shipbuilders that they would produce tanks of AQL quality. This is accomplished through choice of sampling plan as well as by providing for a shift to a tighter sampling plan whenever the shipbuilders' tanks have deteriorated from the agreed upon AQL target.

The probability or assurance of accepting tanks of a specified AQL quality is always high in these plans but not exactly the same for all plans. Ultimately the OC curve determines the percent of lots expected to be accepted and generally the range is from 88 to 99 percent. The tabled AQL's for fraction defective plans run from 0.10 percent to 10 percent and for defects-per-unit plans they run up to 1,000 defects per 100 units. The regulatory agencies will need to specify AQL's for various tank types in order to use these plans.

Typically, AQL's can be determined from historical data (i.e., past data of the process quality average) and the standard AQL could be set equal to this historical average. Other approaches would be to arrive at suitable choices of AQL's from empirical judgment, engineering estimates, experimental tests, or cost analysis. The most useful aid in arriving at an AQL would be to classify tank defects as critical, major or minor according to definitions provided in the standard. Different AQL's could be designated for these groups of defects with major defects being assigned a lower AQL than minor defects.

The tables of MIL-STD-105D also specify different amounts of inspection level (i.e., levels I, 11, and III and Sl$ S2S S3S and S4). Level 11 is designated as normal, while level I is used when less discrimination is needed and level III when more discrimination is needed. The suggested level for tank testing is level II, the normal inspection level.

Given a specified AQL, an inspection level, and a given lot size, MIL-STD-105D gives a normal sampling plan to be used as long as a shipyard builds tanks of AQL quality. It also provides a tightened plan when there is an evident downward shift in tank building quality and a reduced plan when quality is high. These are used in the following circumstances:

1) When normal inspection is in effect, tightened inspection will be used when 2 out of 5 consecutive lots of tanks have been rejected on original inspection (ignoring resubmitted lots).

2) When tightened inspection is in effect, normal inspection will be used when 5 consecutive lots have been considered acceptable on original inspection.

3) When normal inspection is in effect, reduced inspection will be used when 10 consecutive lots have not been rejected on original inspection.

4) When reduced inspection is in effect, normal inspection will be instituted when a lot is rejected or does not meet the acceptance criteria.

5) When tightened inspection is in effect, inspection will be discontinued pending action on quality when 10 consecutive lots remain on tightened inspection.

d. <u>Selection of Plan</u>

An acceptance sampling plan is chosen from the MIL-STD-105D tables by the following procedure:

1) Choose an acceptable quality level (AQL).

2) Select a suitable inspection level (preferably level II).

3) Determine the lot size (i.e., number of tanks in lob.

4) Knowing the lot size and inspection level, obtain a code letter from Table VIII.2.

5) Knowing the code letter, AQL, and using single sampling, read the appropriate sampling plan from Table VIII.3.

6) Determine from the chosen sampling plan the needed sample size and the acceptance and rejection numbers.

7) Using graphs of the OC curve for the chosen sampling plan (see MIL-STD-105D), determine the assurance of accepting a lot at the given AQL.

For example, suppose that a shipowner had contracted for a lot of 10 tanks with an AQL of 1%. From Table VIII.2 it is found that letter 3 plans are required for inspection level II. Table VIII.3 states that the sample size is 3. For AQL = 1.0, the acceptance number is given as O and the

TABLE VIII.2. SAMPLE SIZE CODE LETTERS - MIL-STD-105D

	Special Inspection Levels				General Inspection Levels		
Lot Size	s-1	s-2	s-3	s-4	I	11	111
2-8	A	A	A	A	A	A	B
9-15	A	A	A	A	A	B	C
16-25	A	A	B	B	B	C	D
26-50	A	B	A	C	C	D	E

TABLE VIII.3

MASTER TABLE FOR NORMAL INSPECTION-SINGLE SAMPLING
(Mil. Std. IOSD, Table 11-A)

Sample size code letter	Sample size	0.010 Ac Re	0.015 Ac Re	0.025 Ac Re	0.040 Ac Re	0.065 Ac Re	0.10 Ac Re	0.15 Ac Re	0.25 Ac Re	0.40 Ac Re	0.65 Ac Re	1.0 Ac Re	1.5 Ac Re	2.5 Ac Re	4.0 Ac Re	6.5 Ac Re	10 Ac Re	15 Ac Re	25 Ac Re	40 Ac Re	65 Ac Re	100 Ac Re	150 Ac Re	250 Ac Re	400 Ac Re	650 Ac Re	1000 Ac Re
A	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31
B	3	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45
C	5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	↑
D	8	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	↑	↑
E	13	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	↑	↑	↑
F	20	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	↑	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	↑	↑	↑	↑	↑	↑

MASTER TABLE FOR TIGHTENED INSPECTION-SINGLE SAMPLING
(Mi. Std. 105D. Table II-B)

Sample size code letter	Sample size	0.010 Ac Re	0.015 Ac Re	0.025 Ac Re	0.040 Ac Re	0.065 Ac Re	0.10 Ac Re	0.15 Ac Re	0.25 Ac Re	0.40 Ac Re	0.65 Ac Re	1.0 Ac Re	1.5 Ac Re	2.5 Ac Re	4.0 Ac Re	6.5 Ac Re	10 Ac Re	15 Ac Re	25 Ac Re	40 Ac Re	65 Ac Re	100 Ac Re	150 Ac Re	250 Ac Re	400 Ac Re	650 Ac Re	1000 Ac Re
A	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	27 28
B	3	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	27 28	41 42
C	5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	27 28	41 42	↑
D	8	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	27 28	41 42	↑	↑
E	13	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	27 28	41 42	↑	↑	↑
F	20	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	↓	↓	1 2	2 3	3 4	5 6	8 9	12 13	18 19	↑	↑	↑	↑	↑	↑

MASTER TABLE FOR REDUCED INSPECTION—SINGLE SAMPLING
(Mil. Std. 105D, Table II-C)

Sample size code letter	Sample size	0.010 Ac Re	0.015 Ac Re	0.025 Ac Re	0.040 Ac Re	0.065 Ac Re	0.10 Ac Re	0.15 Ac Re	0.25 Ac Re	0.40 Ac Re	0.65 Ac Re	1.0 Ac Re	1.5 Ac Re	2.5 Ac Re	4.0 Ac Re	6.5 Ac Re	10 Ac Re	15 Ac Re	25 Ac Re	40 Ac Re	65 Ac Re	100 Ac Re	150 Ac Re	250 Ac Re	400 Ac Re	650 Ac Re	1000 Ac Re
A	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↓	↓	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31
B	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	0 2	1 3	2 4	3 5	5 6	7 8	10 11	14 15	21 22	30 31
C	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	0 2	1 3	1 4	2 5	3 6	5 8	7 10	10 13	14 17	21 24	↑
D	3	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	0 2	1 3	1 4	2 5	3 6	5 8	7 10	10 13	14 17	21 24	↑	↑
E	5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	0 1	↑	↓	0 2	1 3	1 4	2 5	3 6	5 8	7 10	10 13	14 17	21 24	↑	↑	↑
F	8	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1	↑	↓	0 2	1 3	1 4	2 5	3 6	5 8	7 10	10 13	↑	↑	↑	↑	↑	↑

Acceptable Quality Levels (reduced inspection)†

↓ = Use first sampling plan below arrow. If sample size equals or exceeds lot or batch size, do 100 percent inspection.
↑ = Use first sampling plan above arrow.
Ac = Acceptance number.
Re = Rejection number.
† = If the acceptance number has been exceeded, but the rejection number has not been reached, accept the lot, but reinstate normal inspection (see 10 1 4).

rejection number as 1. This means that the entire lot of 10 tanks may be accepted if no defective tanks are found in the 3 sampled tanks. However, the entire lot must be rejected if one or more defective tanks are found. Finally, the OC curve for plan B (in Reference 23) could be examined to determine the probability of accepting a lot with an AQL less than or equal to 1%.

e. Definition.of Defect

It is obvious that a definition of what constitutes an acceptable tank is needed. One cannot hope to specify an.AQL, the average quality level, until one defines what is meant by a defective tank. While different solutions are possible, a suggested Criterion would be to use the NKK bad mark system as described and modified in Section VIII.B.2. With this system, each tested tank would receive a weighted defect score. The AQL could then be based on the number of defects per hundred tanks rather than the fraction defective. Thus, the calculated quality level would be based on the following formula:

$$\text{Defects per hundred units} = \frac{\text{NKK defect score}}{\text{Number of tanks inspected}} \times 100$$

In turn, this measure also makes use of the data collection system established in Section VIII.B.2 in that historical data will be available to constantly monitor and refine the AQL's for various tank types.

f. Other Considerations

The sampling plans specified in MIL-STD-105D can be seen to be very useful. Provided a definition of a defective tank can be determined, one needs only to follow the steps outlined in subsection VIII.B.3.d in order to determine a sampling plan. At the same time consideration can be given to reducing or tightening inspection by following the procedures of subsection VIII.B.3.C. There remain, however, a few concepts that need to be clarified when using these plans.

First, the plans are to be used where series of lots of tanks are constructed. Thus, no lot should be reviewed as a single item from the given shipyard. Instead, the quality assurance must be monitored over a given period of time. This will lead to reduced inspection in the good shipyards and tightened inspection in the poor ones.

Secondly, the plans are meant to be used separately for each tank type to be inspected. Thus it is important to keep the tank categories large enough so that the lot sizes are meaningful but small enough so that the definition of tank type is meaningful. As shown in Table VIII.2 lot sizes can be as small as two. Tables in Reference 23 give sampling plans for much larger lot sizes if they are necessary.

Thirdly, different AQL's can be used with each tank type. These AQL's need to be established using the data collected in Section VIII.B.2 or the consensus of the regulatory agencies acting in conjunction with the shipyards and shipowners.

Next, a procedure for choosing a random sample of tanks is needed. .A suggested approach would be for the inspector to randomly choose a specified number of tanks from each type listed in Section VII.B.2. To aid in this selection procedure, a random number table such as that given in Table VIII.4 can be assigned to each inspector. To decide which tank to choose, the inspector merely numbers the tanks and then uses the table. For example, suppose there were 8 tanks of a given type available for inspection and one was *to* be tested. The inspector would number the tanks from 1 to 8 by assigning 1 to the first tank, 2 to the second tank, and so forth. The tank to be tested would be decided by choosing the first number in the table which falls within the range of the tank numbers. In this example, the first number in the table, 8, is chosen, which corresponds to the eighth tank. At the next inspection the inspector would choose the next number down the table, which is 3, and so forth. If there were 20 tanks in the sample, the inspector would examine the first 2 digits in the column of numbers in the table.

Finally, a decision needs to be made on what course of action should be taken when a group of tanks is rejected. One suggestion would be to test all tanks in the lot so that all defects could be corrected. An alternative would be to correct the defects on the inspected sampled tanks and then resubmit the entire lot of tanks to-be reinspected under the acceptance sampling procedure.

4. Concluding Remarks

Acceptance sampling techniques provide the shipbuilding industry with tighter quality control procedures and improved test methodology. Combined with the data collection system described in Section VIII.B.2, this procedure provides specified assurances for accepting tanks of a given quality. Provided a definition of a defective tank can be established and universally accepted, the use of these sampling plans and tables can provide a balanced and economical inspection program.

TABLE VIII. 4. R4NDOM NUMBERS

TEN THOUSAND RANDOM DIGrrs

	00-04	05-09	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49
00	88758	66605	33843	43623	62774	25517	09560	41880	85126	60755
01	35661	42832	16240	77410	20686	26656	59698	86241	13152	49187
02	26335	03771	46115	88133	40721	06787	95962	60841	91788	86386
03	60826	74718	56527	29508	91975	13695	25215	72237	06337	73439
04	95044	99896	13763	31764	93970	60987	14692	71039	34165	21297
05	83746	47694	06143	42741	38338	97694	69300	99864	19641	15083
06	27998	42562	63402	10056	81668	48744	08400	83124	19896	18805
07	82685	32323	74625	14510	85927	28017	80588	14756	54937	76379
08	18386	13862	10988	04197	18770	72757	71418	81133	69503	44037
09	21717	13141	22707	68165	58440	19187	08421	23872	03036	34208
10	18446	83052	31842	08634	11887	86070	08464	20565	74390	36541
11	66027	75177	47398	66423	70160	16232	67343	36205	50036	59411
12	51420	96779	54309	87456	78967	79638	68869	49062	02196	55109
13	27045	62626	73159	91149	96509	44204	92237	29969	49315	11804
14	13094	17725	14103	00067	68843	63565	93578	24756	10814	15185
15	92382	62518	17752	53163	63852	44840	02592	88572	03107	
16	16215	50809	49326	77232	90155	69955	93892	70445	00906	57002
17	09342	14528	64727	71403	84156	34083	35613	35670	10549	07468
18	38148	79001	03509	79424	39625	73315	18811	86230	99682	82896
19	23689	19997	72382	15247	80205	58090	43804	94548	82693	22799
20	25407	37726	73099	51057	68733	75768	77991	72641	95386	70138
21	25349	69456	19693	85568	93876	18661	69018	10332	83137	88257
22	02322	77491	56095	03055	37738	18216	81781	32245	84081	18436
23	15072	33261	99219	43307	39239	79712	94753	41450	30944	53912
24	27002	31036	85278	74547	84809	36252	09373	69471	15606	77209
25	66181	83316	40386	54316	29505	86032	34563	93204	72973	90760
26	09779	01822	45537	13128	51128	82703	75350	25179	86104	40638
27	10791	07706	87481	26107	24857	27805	42710	63471	08804	23455
28	74833	55767	31312	76611	67389	04691	39687	13596	88730	86850
29	17583	24038	83701	28570	63561	00098	60784	76098	84217	34997
30	45601	46977	39325	09286	41133	34031	94867	11849	75171	57682
31	60683	33112	65995	64203	18070	65437	13624	90896	80945	71987
32	29956	81169	18877	15296	94368	16317	34239	03643	66081	12242
33	91713	84235	75296	69875	82414	05197	66596	13083	46278	73498
34	85704	86588	82837	67822	95963	83021	90732	32661	64751	83903
35	17921	26111	35373	86494	48266	01888	65735	05315	79328	13367
36	13929	71341	80488	89827	48277	07229	71953	16128	65074	28782
37	03248	18880	21667	01311	61806	80201	47889	83052	31029	06023
38	50583	17972	12690	00452	93766	16414	01212	27964	02766	28786
39	10636	46975	09449	45986	34672	46916	63881	83117	53947	95218
40	43896	41278	42205	10425	66560	59967	90139	73563	29875	79033
41	76714	80963	74907	16890	15492	27489	06067	22287	19760	13056
42	22393	46719	02083	62428	45177	57562	49243	31748	64278	05731
43	70942	92042	22776	47761	13503	16037	30875	80754	47491	96012
44	92011	60326	86346	26738	01983	04186	41388	03848	78354	14964
45	66456	00126	45685	67607	70796	04889	98128	13599	93710	23974
46	96292	44348	20898	02227	76512	53185	03057	61375	10760	26889
47	19680	07146	53951	10935	23333	76233	13706	20502	60405	09745
48	67347	51442	24536	60151	05498	64678	87569	65066	17790	55413
49	95888	59255	06898	99137	50871	81265	42223	83303	48694	81953

IX. KEY FINDING, CONCLUSIONS AND RECOMMENDATIONS

From the literature search, visits and inquiries to shipbuilders and regulators worldwide, and the laboratory evaluations performed during this study, many worthwhile observations and discoveries were made. These key findings permitted conclusions to be drawn and important recommendations to be made. The key findings from this study are highlighted below followed by our conclusions and recommendations. More details on the work which produced these results are found in preceding sections.

A. Key Findings

- Tank testing methods and the rules governing tank testing are similar worldwide. Japanese shipbuilders utilize the vacuum box more than shipbuilders in other countries. Minor differences in the rules affect (1) the types of tanks that can be air tested, (2) the scheduling of tightness testing relative to the application of coatings, and (3) the scheduling of hydrostatic testing relative to sea trials.

- Two methods are predominant in the tightness testing of ship tanks. These are a hydrostatic test and a low pressure air test with soap as the detection fluid.

- Under laboratory conditions, the minimum detectable hole size is comparable for the hydrostatic test and the 2.0 psig air and soap test. Equal sensitivity is achieved with water at 24 psig (55 feet liquid head) and air (with soap) at 2.0 psig.

- A hydrostatic test does not subject the tank to its design loads, and very few structural defects are discovered by hydrostatic testing.

- Air tests are not suitable for structural testing of integral ship tanks; however, to gain confidence in analytical methods used for ship analysis, measured and calculated deflections could be compared for either an air test or a hydrostatic test.

- For any new test method, shipbuilders emphasize increased productivity, whereas regulators emphasize improved leak visibility.

- Ultrasonics can be used to detect flaws during an air test; however, its sensitivity is inferior to the use of soap for leak detection. The minimum detectable hole size using ultrasonics and air at 2.0 psig is about 8 roils.

- The minimum detectable hole size using a dye penetrant is comparable to a hydrostatic or air and soap test. This method offers improved visibility but does not increase productivity.

- Thermography is not a viable method for the tightness testing of integral ship tanks. Measurable temperature gradients in the tank wall at a flaw, require large differences in temperature between the tank walls and the test fluid (chilled or heated air). These differences are not practical to achieve and maintain in large ship tanks.

- Ship tank coatings and primers (applied with a spray gun) sealed flaws (drilled holes) smaller than 70 mills in diameter. These flaws remained sealed at pressures up to 150 psig.

- Statistics are not now used in tank testing.

B. <u>Conclusions</u>

- Criteria for acceptance of new tank testing methods are different for shipbuilders and regulators. The criterion for shipbuilders tist include increased productivity in shipbuilding. The criterion for regulators must include increased leak visibility.

- The hydrostatic test should not be regarded as a structural test of ship tanks.

- Greater assurance of tank tightness is provided by a low pressure air and soap test than by a hydrostatic test.

- There are many methods of leak detection. However, none improve productivity relative to the low pressure air and soap test and also provide equal or greater leak detection sensitivity.

- Coatings and primers will effectively seal flaws (in a laboratory environment) which are much larger than the minimum flaw size detectable by current tightness testing methods.

- The reliability of coatings to “permanently” seal small leaks under conditions more closely approximating those in the shipyard and in service is unknown.

- Only ultrasonic detection methods show potential for improving productivity in ship tank testing. The sensitivity of this method is less than that achieved with air and soap. For this method to be accepted as a replacement test, sensitivity requirements must either be reduced or the use of coatings to seal small flaws (smaller than 8 mil diameter equivalent hole size) must be accepted.

- A rigid statistical method, which provides known assurance levels, is practical for the tightness testing of ship tanks. A testing methodology, based upon statistical sampling techniques, is suggested for ship tank testing. This methodology provides high assurance levels.

C. Recommendations

1) Change the ABS Rules as follows:

   o Relax the tank testing requirements for bulkheads separating common cargoes.

   o Accept the air and soap test in place of a hydrostatic test for all tank tightness testing. Suggested revisions to the ABS Rules, 1977 Edition, are summarized in Table 1X.1.

2) Adopt a record keeping procedure for tank testing from which a statistical sampling inspection procedure can be developed.

3) Investigate the reliability of coatings for sealing small leaks.

4) Conduct field testing of ultrasonics for leak detection in a shipyard environment.

TABLE IX.1

PROPOSED REVISION OF THE ASS RULES FOR TANK TESTING

ORIGINAL WORDING *	PROPOSED REVISION	RATIONAL FOR REVISION
Section 7: Bottom Structure 7.23 Testinq Double bottoms are to be tested with a head of water up to the freeboard deck, the bulkhead deck, or to the bighest point to which the contents may rise under service conditions, whichever is highest. This test may be made either before or after the vessel is launched. Air testing may, at the discretion of the Surveyor, be accepted as an alternative to hydrostatic testing for tanks intended for the exclusive carriage of water ballast. In such cases selective hydrostatic testing of the tanks is required is considered necessary by the Surveyor. In general all fillet weld boundary connections, erection joints. and boundaries of manhole covers, ctc. are to be examined under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. Hydrostatic testing may be conducted after the application of Special coatings, provided all welded connections are surveyed prior to application of the coatings and found to be to the satisfaction of the Surveyor. Air testing, where permitted above, is to be carried out prior to the application of the coatings and found to be to the satisfaction of the Surveyor. Air testing, where permitted above, is to be carried out prior to the application of special coating to the fillet weld boundary connections and erection joints. The procedure of air testing is to be submatted for review. Cement work, ceiling, etc. is not to be applied until after testing 1s completed. Air pipes, sounding pipes and all other connections outside the double bottom are to be fitted before testing. Where engines or thrust blocks are bolted directly to the inner bottom, the tanks in way of the same are to be tested after the machinery is fitted in place.	Section 7: Bottom Structure 7.23 Testing Double bottoms must be tested for tightness using either a hydrostatic or an air test. The hydrostatic test must be performed with a head of water up to the free-hard deck, the bulkhead deck, or to the highest point to which the contents may rise under service conditions, whichever is highest This test may be made either before or after the vessel is launched. Hydrostatic testing may be conducted after the application of special coatings, provided all welded connections are surveyed prior to application of the coatings and found to be to the satisfaction of the Surveyor. The air test must be conducted with a minimum pressure differential of 2.0 psig across the tank boundary. In general, aIl fillet weld boundary Connections, erection joints, and boundaries of manhole covers, etc are to be examined under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. Air testing is to be carried out prior to the application of special coatings to the weld boundary connections and erection joints. The procedure for air testing is to be submitted for review. Cement work, ceiling. etc. is not to be applied until after testing is completed. Air pipes, sounding pipes and all other connections outside the double bottom are to be fitted before testing. Where engines or thrust blocks are bolted directly to the inner bottom, the tanks in way of the same are to be tested after the machinery is fitted in place.	Under ABS rules, hydrostatic testing is used to demonstrute structural adequacy only for the case of new vessel designs where L is greater than 230 m 1750 ft]. For all other cases, hydrostatic testing is performed to demonstrate tank tightness. At present, the Rules state that ther Substitution of an air test in place of a hydrostatic test in left to the discretion of the Surveyor. It is recommended that for tightness testinq the choice of using air or water be left to the shipyard but with the stipulation that, if an air test is to be used, the shipyard submit a test procedure to the Surveyor for his approval. It is also recommended that the air test be conducted with a minimum pressure differential 2.0 psig across the tank boundary. Under laboratory conditions, the minimum detectable hole size is comparable for the hydrostatic test and the 2.0 psig air and soap test. Equal sensitivity is achieved with water at 24 psig (55 ft liquid head) and air (with soap) at 2.0 psig.
Section 13: Deep Tanks 13.11 Testing Deep tanks are to be tested with a head of water to the overflow, to the load line or two-thirds of the distance from the top of the tank to the bulkhead or freeboard deck, whichever is greatest. Testing may be conducted after the application of special coatings, provided all welded connections are surveyed prior to application of the coatings and found to be to the satisfaction of the Surveyor. Hydrostatic testing may be conducted either before or after the vessel is launched. Air testing may. at the discretion of the Surveyor. be accepted as an alternative to hydrostatic testinq provided the tanks are not intended for the carriage of liquids other than water ballast. In such cases, selective hydrostatic testing of the tanks is required as considered necessary by the Surveyor. In general, all fillet weld boundary connections. erection joints. and boundaries of manhole covers, etc. are to be examined under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. Air testing is to be carried out before special coatings are applied to the fillet weld boundary connections and erection joints. The procedure of air testing as to be submitted for review. Cement work, ceiling, etc. is not to be applied until after testing is completed. Air pipes, sounding pipes, and all other connections are to be fitted before testing.	Section 13: Deep Tanks 13.11 Testing Deep tanks must be tested for tiqhtness using either a hydrostatic or an air test. The hydrostatic test must be performed with a head of water to the overflow, to the load line or two-thirds of the distance from the top of the tank to the bulkhead or free-board deck, whichever is greatest. Testing may be conducted after the application of special coatings, provided all welded connections are surveyed prior to application of the coatings and found to be to the satisfaction of the surveyor. Hydrostatic testing may be conducted either before or after the vessel is launched. The air test must be performed with a minimum pressure differential of 2.0 psig across the tank boundary. In general. all fillet weld boundary connections, erection joints, and boundaries **of** manhole covers. etc. are to be examined under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. Air testing is to be carried out before special coatings are applied to the fillet weld boundary connections and erection joints. The procedure of air testing is to be submitted for review. Cement work, ceiling, etc. is not to be applied until after testing is completed. Air pipes, sounding pipes, and all other connections are to be fitted before testing.	Same as above.

(Costinued)

TABLE IX.1

PROPOSED REVISION OF THE ABS RULES FOR TANK TESTING (Continued)

ORIGINAL WORDING *	PROPOSED REVISION	RATIONAL FOR REVISION
Section 22: Vessels Intended to Carry Oil In Bulk 22.13 Testing 22.13.1 Testing of Unprotected Tanks All cargo, ballast and cofferdam spaces are to be tested before the vessel is launched or when in drydock With a head of water 1.22 m (4 ft) above the deck at side forming the crovn of the tanks in vessels of 61 m [200 ft] length, and 2.44 m (8 ft) above, in vessels of 122 m (400 ft) length and over: for intermediate lengths, intermediate heights above the deck are to be used. The test head is not to be less than the distance to the tops of the hatches. Air testing may, at the discretion of the Surveyor, be accepted as an alternative to hydrostatic testing except as indicated below. In general. all fillet weld boundary connections and erection joints are to be examxned under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. The procedure for air testing is to be submitted for review. Bulkheads separating cargo tanks . from cofferdams, pump rooms, machinery spaces, or tanks arranged exclusively for ballast are to be hydrostatically tested as Indicated above, but this testing may be carried out after the vessel is afloat. In additxon, in order to demonstrate structural adequacy, in the case of new vessel designs where L is greater than 230 m (750 ft), a pattern for hydrostatically testing the tanks may be required, giving due consideration to the combination of load distribution and draft which would most likely result in high calculated structural stresses under actual service conditions. 22.13.2 Testing of Protected Tanks where one or more effective methods of corrosion control are adopted in the tanks the testing procedures outlined in 22.13.1 may be modified to permit the hydrostatic testing of the tanks to follow the application of special coatings, provided all welded connections are surveyed prior to application of special coatings and found to be to the satisfaction of the Surveyor, and further provided that alternate arrangements are considered to be at least as effective as those required by 22.13.1. Air testing of protected tanks, where permitted by 22.13.1, is to be carried out prior to the application of coatings to the fillet weld boundary connections and erecticm joints.	**Section 22: Vessels Intended to Carry Oil In Bulk** 22.13.1 Testing of Unprotected Tanks All cargo, ballast and cofferdam spaces are to be tested for tiahtness usina either a hydrostatic or an air test. The hydrostatic test must be performed before the vessel is launched or when in drydock with a head of water 1.22 m (4 ft) above the deck at side forming the crown of the tanks in vessels of 61 m (200 ft) length, and 2.44 m (8 ft) above, in vessels of 122 m (400 ft) length and over: for intermediate lengths, intermediate heights above the deck are to be used. The test head is not to be less than the distance to the tops of the hatches. The air test must be conducted with a minimum pressure differential of 2.0 psig across the tank boundary. In general, all fillet weld boundary connections and erection joints are to be examined under air test by use of a suitable leak detection solution: other welded joints, at the discretion of the Surveyor, may also be required to be similarly examined. The procedure for air testing is to be submitted for review. At the discretion of the Surveyor hydrostatic testing of bulkheads separating cargo tanks from cofferdams, pump rooms, machinery spaces, or tanks arranged exclusively for ballast may be required. This test is to be performed as indicated above, bnt it may be carried out after the vessel is afloat. In addition, in order to demonstrate structural adequacy, in the case of new vessel designs where L is greater than 230 m (750 ft), a pattern for hydrostatically testing the tanks may be required, giving due consideration to tbe combination of load distribution and draft which would most likely result in high calculated structural stresses under actual service conditions. 22.13.2 Testing of Protected Tanks Where one or more effective methods of corrosion control are adopted in the tanks, the testing procedures outlined in 22.13.1 may be modified to permit the hydrostatic testing Of the tanks to follow tbe applicatio of special Coatings, provided all welded connections are surveyed prior to application of the coatings and found to be to the satisfaction of the Surveyor, and further provided that alternate arrangements are considered to be at least as effective as those required by 22.13.1. Air testing of protected tanks is to be carried out prior to the application of coatings to the fillet weld boundary connections and erection joints.	Under ABS rules, hydrostatic testing is used to demonstrate structural adequacy only for the case of new vessel designs where L is greater than 23o m (750 ft). For all other cases, hydrostatic testing is performed to demonstrate tank tightness. At present, the Rules state that the substitution of an air test in place of a hydrostatic test is left to the discretion of the Surveyor. It is recommended that for tightness testing the choice of using air or water be left to the shipyard but with the stipulation that, if an air test is to be used, the shipyard submit a test procedure to the Surveyor for his approval. It is also recommended that the air test be conducted with a minimum pressure differential of 2.0 psig across the tank boundary. Under laboratory conditions, the minimum detectable hole size is comparable for the hydrostatic test and the 2.0 psig air and soap test. Equal sensitivity is achieved with water at 24 psig (55 ft liquid head) and air (with soap) at 2.0 psig.
Section 23: Vessels Intended to Carry Liquefied Gases 23.19 Testing Double bottom tanks are to be tented in accordance with 7.23. Side tanks and wing tanks are to be tested in accordance with 13.11 and 7.23, respectively, except that for ore carriers, the side and wing tanks are to be hydrostatically tested to the heads given in 22.13. Tanks intended for the carriage of oil carqoes and associated cofferdams are to be tested in accordance with 22.13.	**Section 23: Vessels Intended to Carry Liquefied Gases** No revisions necessary.	

*The original wording of the ABS Rules is taken from the 1977 rule book.

APPENDIX A

LITERATURE SEARCH ALGORITHMS

The literature search was conducted in two phases. The object of the initial survey was to identify leak detection techniques currently in use. This search emphasized detection methods used in the shipbuilding and inland tank industries. The object of a later survey concentrated on equipment and techniques either used for leak testing or which might be adapted for leak testing. The techniques identified during the initial search were used as key words in the later search.

A computer assisted literature search begins with the selection of key words. Some data bases have a thesaurus of legal key words, but most do not. In this case, words in the title or in the abstract are used as key words. The search proceeds by scanning the words in the title or abstract of all papers in the data base for matches with one of the user's key words. The user can run several searches and create several files of citations. Then the files may be manipulated using the standard boolean operators: and, or, not, etc. This enables the user to, for example, obtain only those citations which were identified. in every one of several searches.

The key words selected for the initial search are given in Table A.l. The dash behind some of the key words is used so that all forms of the key-word can be detected. For example, papers having keywords of leak, leaks, leaking, and leakage would be detected using the keyword leak-. The citations associated with each key work listed in a given set of brackets were "or'ed or combined into a common file. Later they were "and"ed with the other two similar files. Thus, a paper was selected only if it had at least one key word in each of the vertical columns of key words. Two independent searches were made as indicated in the Table. The first was more general, and was intended to find papers dealing with leak or tightness testing or ships or inland tanks. The second was more specific and sought papers dealing with various forms of air and water tests.

The later computer search was conducted in a similar fashion to the earlier one. It concentrated on leak detection schemes identified during the initial search. The keywords for this search are found in Search 3 of Table A.l.

TABLE A. 1. KEY WORDS FOR THE COMPUTER ASSISTED SEARCHES

Search 1

LEAK- TIGHT-	and	TEST- EXAMIN- INSPECT-	and	VESSEL- TANK- SHIP-

Search 2

AIR WATER PNEUMATIC- HYDRO- PRESSURE- STRUCTUR-	and	TEST- INSPECT- EXAMIN-	and	VESSEL- TANK- SHIP-

Search 3

DYE- PENETRANT- HELIUM HALOGEN ULTRASONIC- ACOUSTIC SONIC THERMAL THERMOG-	and	LEAK TIGHTNESS LEAKAGE	and	LOCATION DETECTION TESTING

APPENDIX B

ORGANIZATIONS RESPONDING TO WRITTEN INQUIRIES

Regulatory Agencies

American Bureau of Shipping

U. S. Coast Guard

.U. S. Navy (NAVSEC)

Bureau Veritas

Germanisher Lloyd

Lloyds Register

Nippon Kaiji Kyokai

Shipbuilders

USA:	General Dynamics/Quincy Shipbuilding Division Newport News Shipbuilding Company Sun Shipbuilding and Drydock Company Todd Pacific Shipyards Corporation, Los Angeles Division
Canada:	Davie Shipbuilding, Ltd.
France:	Constructions Navales et Industrielles de la Mediterranee Chan Tiers de l'Atlantique
Germany:	AG "Weser" Bremen Bremen Vulkan Schiffbau and Maschinenfabrik Thyssen Nordseewerke Emden
Japan:	Hitachi Shipbuilding and Engineering Company, Ltd. Ishikawajima-Harima Heavy Industries Company, Ltd. Kawasaki Heavy Industries, Ltd.
Norway:	Moss-Rosenberg Verft A/S
Sweden:	AB Goetaverken Kockums Shipyard
United Kingdom:	Govan Shipbuilders, Ltd. Sunderland Shipbuilders, Ltd.

APPENDIX C

AMERICAN BUREAU OF SHIPPING RATIONALE BEHIND RULE FOR INTEGRAL TANK TESTING

a. Purpose - Integral tanks are tested only to determine tightness, except for oil tankers over 750 ft in length. Here hydrostatic tests of the cargo tanks are for verification of structural strength as well as tightness.

Rationale - For oil tankers under 750 ft in length, ship scantlings are determined by ABS formula. A long history of successful designs by these formulas has established confidence in them and in the values assigned to their coefficients. For tankers over 750 ft in length, finite element methods are used to establish ship scantlings and ABS requires the hydrostatic test for confirmation of the structure in the cargo tank area.

b. Selection of Test Type - ABS requires a hydrostatic test for critical boundaries. Critical boundaries are those in which leaks could be dangerous or very costly in terms of damage produced or the expense of repair.

Rationale - ABS has greater confidence in a hydrostatic test for leak detection. Confidence is based on many years of successful use of water and easier sighting of leaks by the surveyor. LNG ships require complete hydrostatic testing of integral tanks for safety reasons and for compliance with IMCO guidelines.

c. Testing Scheduling Relative to Application of Special Coatings* - Hydrostatic tests are permitted after the application of special coatings; air tests must be performed before special coatings are applied to the welds which are required to be inspected.

Rationale - Hydrostatic tests are permitted after special coatings are applied because such a test closely represents future service conditions. Air tests are low pressure tests which do not simulate service conditions and so must be performed before the coatings are applied. ABS believes that most special coatings may seal some openings during an air test that will subsequently leak in service when subjected to a head of dense liquid.

d. Inspection Requirements for Different Joints - "In general, all fillet weld boundary connections, erection joints, and boundaries of manhole covers, etc., are to be examined under air test by use of a suitable leak detection solution; other welded joints, at the discretion of the surveyor, may also be required to be similarly examined." No guidance is given for hydrostatic tests. A visual examination (before coatings are applied) or automatic butt and seam welds is usually judged by the local surveyor to be sufficient to assure tank tightness in these regions.

*special coatings are approved by ABS and are applied to reduce corrosion in the ship tanks. Most common coatings are zinc and epoxy.

Rationale - Experience has shown that automatic butt and seam welds seldom leak, except at obvious flaws which are caught by visual inspection, and that most leaks occur in manual fillet welds, erection joints, and penetrations. More explicit inspection requirements are set for air tests because a close visual examination is required to detect leaks. Leaks are more easily detected, without close inspection, during a hydrostatic test.

e. Decisions by the Local Surveyor - The local surveyor is permitted the freedom to decide whether to permit air in lieu of water for ballast tanks and also whether or not to require detailed examination of automatic butt and seam welds.

Rationale - The local surveyor best understands practice in the shipyard and is permitted to choose the test type for certain noncritical tanks and *to* omit inspection for leaks of certain joint types when he believes it is justified.

APPENDIX D

FLOW RATE MEASUREMENTS THROUGH CAPILLARY TUBES

Air Flow Rate Measurements Through Capillary Tubes

Tests were performed to establish the flow rate of air through a capillary tube of known length and diameter for various pressure differentials across the length of the tube. The purpose of these tests was to establish an estimate of the amount of air passing through a typical hole flaw and determine how much air flow through the hole is required for detection of the hole using one of the various detection methods. A special test apparatus was constructed to measure the air flow rate through a capillary tube.

Pictured in Figure D.1 is a schematic drawing of the test apparatus used to measure the flow rate of air through a capillary tube. The basic system consists of five components. These are 1) air pressure regulators, 2) a pressure chamber used as a pressure reservoir, 3) a fast-opening solenoid valve, 4) a capillary tube, and 5) an overflow tank used for collecting air that flows through the capillary.

The operating procedure for the test apparatus is as follows. Air inside the pressure chamber is held at a constant pressure level. The solenoid valve located between the pressure chamber and the capillary is opened to allow air to flow from the pressure chamber through the capillary tube. By maintaining a constant air pressure in the pressure chamber, the air flow through the tube is held constant. The flow rate of air through the tube is then determined by measuring the change in mass of the air in the overflow tank over a known time period.

The change in mass of air in the overflow tank can be calculated using the Ideal Gas Equation:

$$Pv = mRT \qquad (1)$$

where

P = air pressure in the overflow tank
v = volume of the overflow tank
m = air mass in the overflow tank
R = Universal Gas Constant
T = air temperature in the overflow tank

Since the above equation holds true both before and after the air has flowed through the capillary and into the overflow tank, then the change in air mass in the tank is:

$$m_{after} - m_{before} = \frac{V}{R}\left(\frac{P_{after}}{T_{after}} - \frac{P_{before}}{T_{before}}\right) \qquad (2)$$

Dividing the mass change calculated in Eq. 2 by the time that the air was allowed to flow through the capillary yields the flow rate of air through the tube.

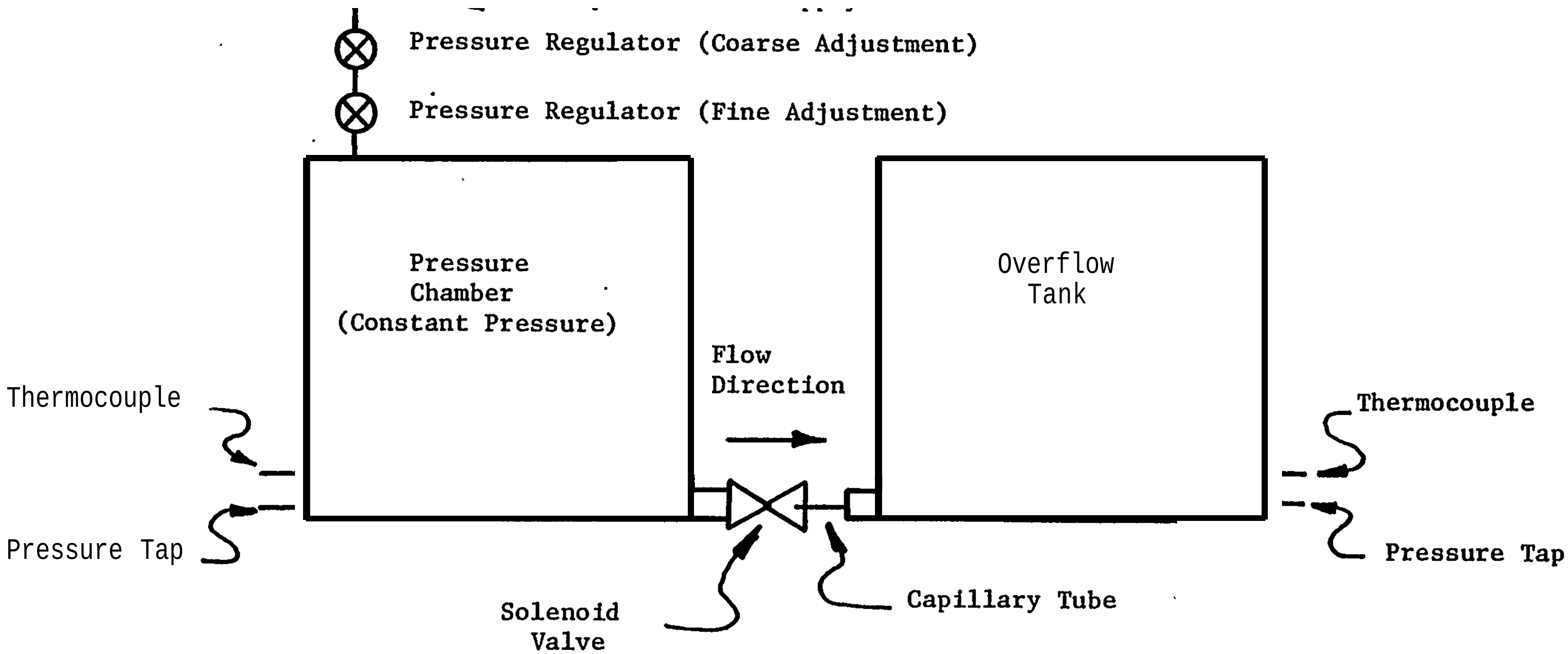


FIGURE D-1. AIR AND WATER LEAK TEST APPARATUS SCHEMATIC

During the actual flow calibrations, the air pressure in the pressure chamber was not maintained exactly constant but instead fluctuated by as much as ±0.5%. This introduced some slight error in the calibrations. In addition, as the air passed through the capillary and into the overflow tank, the air pressure inside the tank increased causing an increase in the resistance to air flow. This increase in the air pressure was limited to less than 1.0% of the pressure drop across the length of the capillary tube to minimize error.

Water Flow Rate Measurements Through Capillary Tubes

For calibrations of water flow through capillary tubes, the apparatus pictured in Figure D.1 was used. The procedure was the same as for the air calibrations except that the pressure chamber was initially filled with water. The flow rate was determined by weighing the amount of water collected in the overflow tank during a given period of time.

As with the air calibrations, the water pressure in the pressure chamber varied no more than ±0.5%. The overflow tank was opened to the atmosphere so, unlike the air flow calibrations, there was no increase in the overflow tank pressure during the test period.

APPENDIX E

SUMMARY TABLE OF TESTS ON WELDMENTS

TABLE E.1

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Hole Number	Pressure. Level* for Leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure LeveL* for Leak Detection with Water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
Carbo Zinc 11 with Carbo-linc 191 HB (Carboline International	1	1	1.0	ND	10.0	ND
	1	2	1.0	ND	5.()	ND
	1	3	1.0	ND	5.0	ND
	1	4	2.0	ND	5.0)	ND
	1	5	30.0	ND	50.0	ND
	1	6	50.0	ND	ND	ND
Not Painted	2	1	10.0		40.0	
	2	2	10.0		40.0	
	2	3	20.0		50.0	
	2	4	10.0		ND	
	2	5	10.0		ND	
	2	6	10.0		50.0	
HS Tank Primer and Coating 24471 (Devoe and Raynolds)	3	1	2.0	ND	10.0	ND
	3	2	2.0	ND	10.0	ND
	3	3	2.0	20.0	5.0	40.0
	3	4	5.0	NO	20.0	ND
Hempel 1540 (Hempel's Marine Paints)	4	1	100	ND	1.0	ND
	4	2	1.0	ND	2 . 0	ND
	4	3	1.0	ND	20.0	

*Maximum pressure level of 50 psi.
ND - Not detected.
( ) - Indicates name of paint suppller.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Note Number	Pressure Level * for leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure level* for leak Detection with Water (psi)	
			Before Paint	Actor paint	Before Paint	After paint
Zinc Primer 30207 with Tank Coating 21556 (Devoe and Raynolds)	5	1	1.0	ND	2.0	ND
	5	2	1.0	ND	1.0	ND
Carboline 191 HB (Carboline International)	6	1	1.0	ND	1.0	ND
	6	2	1.0	ND	1.0	ND
	6	3	1.0	ND	1.0	ND
	6	4	1.0	ND	1.0	ND
	6	5	5.0	ND	ND	ND
Carboline 191 HB (Carboline International)	7	1	1.0	ND	1.0	ND
	7	2	1.0	ND	1.0	ND
	7	3	1.0	ND	1.0	ND
	7	4	1.0	ND	1.0	ND
	7	5	5.0	NO	10.0	ND
Hempel 1540 (Hempel's Marine Paints)	8	1	1.0	ND	1.0	ND
	8	2	1.0	ND	1.0	ND
	8	3	1.0	NO	1.0	ND
	8	4	1.0	ND	1.0	ND
	8	5	1.0	ND	1.0	ND
	8	6	1.0	ND	1.0	ND
	8	7	1.0	ND	5.0	ND

*Maximum pressure level of 50 psi.
ND - Not detected.

( ) - Indicates name of paint supplier.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Hole Number	Pressure Level* for Leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure Level* for Leak Detection with Water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
Hempel 1540 (Hempel's Marine Paints)	9	1	1.0	ND	1.0	ND
	9	2	1.0	ND	1.0	ND
	9	3	1.0	ND	1.0	ND
	9	4	1.0	ND	1.0	ND
	9	5	1.0	ND	1.0	ND
	9	6	1.0	ND	1.0	NO
Carbo Zinc 11 with Carboline 191 HB (Carboline International)	10	1	1.0	ND	1.0	ND
	10	2	1.0	ND	1.0	ND
	10	3	1.0	ND	1.0	ND
	10	4	1.0	ND	1.0	ND
	10	5	1.0	ND	1.0	ND
	10	6	1.0	ND	1.0	ND
	10	7	1.0	ND	2.0	ND
Carbo Zinc 11 with Carbomastic 15 (Carboline International)	11	1	1.0	ND	1.0	ND
	11	2	1.0	ND	1.0	ND
	11	3	1.0	ND	1.0	ND
	11	4	1.0	ND	1.0	ND
	11	5	1.0	ND	1.0	ND
	11	6	40.0	ND	ND	ND

*Maximum pressure level of 50 psi.
ND - Not detected.

( ) - Indicates name of paint supplier.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	HOLC Number	Pressure Level* for leak Dectection with Air and Tercetyl soap solution (psi)		Pressure Level* for leak Detection with Water (psi)	
			Before Paint	After Paint.	Before Paint	After Paint.
Carbo Zinc 11 with Carbomastic 15 (carboline International)	12	1	1.0	ND	1.0	ND
	12	2	1.0	ND	1.0	ND
	12	3	1.0	ND	1.0	ND
	12	4	1.0	ND	40.0	ND
Carboline 187 HFP (Carboline International)	13	1	1.0	ND	1.0	ND
	13	2	1.0	ND	1.0	ND
	13	3	1.0	ND	1.0	ND
	13	4	1.0	ND	1.0	ND
	13	5	1.0	ND	1.0	ND
	13	6	1.0	ND	1.0	ND
	13	7	1.0	ND	1.0	ND
	13	8	1.0	ND	ND	ND
Phenoline 373 (Carboline International)	14	1	1.0	ND	1.0	ND
	14	2	1.0	ND	1.0	ND
	14	3	1.0	ND	1.0	ND
	14	4	1.0	ND	1.0	ND
	14	5	1.0	ND	2.0	ND
Carboline 187 HFP (Carboline International)	15	1	1.0	ND	1.0	ND
	15	2	2.0	ND	2.0	ND

*Maximum pressure level Of 50 Psi.
ND - Not detected.

( ) - Indicates name of paint supplier.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Hole Number	Pressure Level* for Leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure Level* for Leak Detection with Water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
Carboline 187 HFP (Carboline International)	15	3	10.0	ND	20.0	ND
Carboline 375 (Carboline International)	16	1	1.0	ND	1.0	ND
	16	2	1.0	ND	1.0	ND
	16	3	1.0	20.0	1.0	20.0
	16	4	1.0	20.0	1.0	20.0
	16	5	1.0	ND	1.0	ND
	16	6	1.0	ND	1.0	ND
	16	7	1.0	ND	1.0	ND
	16	8	1.0	ND	10.0	ND
Tank Primer 20247 with Tank Coating 21556 (Devoe and Raynolds)	17	1	1.0	ND	1.0	ND
	17	2	1.0	30.0	1.0	10.0
	17	3	1.0	40.0	1.0	20.0
	17	4	1.0	40.0	1.0	20.0
	17	5	1.0	ND	1.0	ND
	17	6	1.0	ND	ND	ND
Tank Primer 20247 with Tank Coating 21556 (Devoe and Raynolds)	18	1	1.0	40.0	1.0	40.0
	18	2	1.0	ND	1.0	ND
	18	3	1.0	ND	1.0	ND
	18	4	1.0	[illegible]	1.0	ND

*Maximum pressure level of 50 psi.
ND - Not detected.

( ) - Indicates name of paint supplier

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Hole Number	Pressure Level* for Leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure Level * for Leak Dectection with Water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
Tank Primer 20247 with Tank Coating 21556 (Devoe and Raynolds)	18	5	1.0	ND	1.0	ND
	18	6	1.0	ND	1.0	N D
	18	7	1.0	1.0	1.0	1.0
	18	8	1.0	ND	1.0	
	18	9	1.0	ND	1.0	ND
	18	10	1.0	ND	1.0	ND
	18	11	l.0	ND	2.0	ND
	18	12	1.0	ND	1.0	ND
Tank Primer 20247 with Anti-Corrosive 23004 (Devoe and Raynolds)	19	1	1.0	ND	1.0	ND
	19	2	1.0	ND	1.0	ND
	19	3	5.0	ND	20.0	ND
Tank Primer 20247 with Anti-Corrosive 23004 (Devoe and Raynolds)	20	1	1.0	ND	1.0	ND
	20	2	1.0	ND	1.0	ND
	20	3	1.0	ND	1.0	ND
	20	4	1.0	ND	1.0	ND
	20	5	1.0	ND	1.0	ND
	20	6	1.0	ND	1.0	ND
	20	7	1.0	ND	1.0	ND
	20	8	1.0	ND	1.0	ND
	20	9	1.0	1.0	1.0	1.0

*Maximum pressure level of 50 psi.
ND - Not detected.

( )'- Indicates name of paint supplier.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint Coating	Specimen Number	Hole Number	Pressure Level* for Leak Detection with Air and Tercetyl soap Solution (psi)		Pressure Level* for Leak Detection with water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
Zinc Primer 30207 with Tank Coating 21556 (Devoe and Raynolda)	21	1	1.0	ND	1.0	N D
	21	2	1.0	ND	1.0	N D
	21	3	1.0	ND	1.0	ND
	21	4	1.0	ND	1.0	ND
	21	5	1.0	ND	1.0	ND
	21	6	1.0	ND	1.0	ND
Zinc Primer 30207 with Anti-Corrosive 23004 (Devoe and Raynolds)	22	1	1.0	ND	1.0	ND
	22	2	1.0	ND	1.0	ND
	22	3	1.0	ND	1.0	ND
	22	4	l.0	5.0	1.0	5.0
	22	5	1.0	5.0	1.0	2.0
Zinc Primer 30207 with Anti-Corrosive 23004 (Devoe and Raynolds)	23	1	1.0	ND	1.0	ND
	23	2	1.0	ND	1.0	ND
	23	3	1.0	NO	1.0	NO
	23	4	1.0	ND	1.(I	ND
	23	5	5.0	ND	ND	N D

*Maximum pressure level of 50 psi.
ND - Not detected.

( ) - Indicates name of paint supplier.

TABLE E.1 (Continued)

EFFECTS OF PAINT ON LEAK DETECTION AT WELD FLAWS

Paint coating	Specimen Number	Hole Number	Pressure level* for leak Detection with Air and Tercetyl Soap Solution (psi)		Pressure Level* for Leak Detection with water (psi)	
			Before Paint	After Paint	Before Paint	After Paint
HS Tank Primer and Coating 24471 (Devoe and Raynolds)	24	1	1.0	ND	1.0	ND
	24	2	1.0	ND	1.0	ND
	24	3	1.0	ND	1.0	ND
	24	4	1.0	ND	1.0	ND
	24	5	1.0	ND	1.0	ND
	24	6	2.0	ND	1.0	ND
	24	7	10.0	ND	ND	N D

*Maximum pressure level of 50 Psi.
ND - Not detected.

( ) - Indicates name of paint

APPENDIX F

REFERENCES

1. J. W. Marr, "Leakage Testing Handbook, " NASA-CR-952, April 1968.

2. C. E. Betz, PRINCIPLES OF PENETRANTS, published by the Magnaflux Corporation, Chicago, 1963.

3. WELDING INSPECTION, published by the American Welding Society, New York, 1968.

4. Y. A. Glaskov and E. P. Bruevich, "Capillary Methods of Detecting Leaks in Tubing Lines of Liquid Systems," Soviet Journal of Nondestructive Testing Vol 12, No. 3, March 1977, pp 312-314.

5. Anon., "Fluorescent Penetrant Test Prevents Leaking Dishwashers," Assembly Engineering, Vol 19, No. 2, Feb. 1976, p 42.

6. Anon., "Penetrant (Leak) Test Lowers Time and Cost of Float (Ball) Inspection," Tooling and Production, Vol 39, No. 9, Dec. 1973, p 52.

7. J. R. Alburger, "Leak Testing with Dyed Liquid Tracers," presented at the American Society for Nondestructive Testing National Convention in Houston, Texas, Sept. 1976.

8. W. H. Burrows and L. W. Elston, "Tracer Sensitive Tapes," Final Technical Report for Project A-1308, Georgia Institute of Technology, NASA-CR-123501, Nov. 1971.

9. "Fluorescent Tracer Techniques," Bulletin from Shannon Luminous Materials Company, Los Angeles, California.

10. J. L. Brown, "Diffusion of Trace Gases for Leak Detection in Aerospace Systems," NASA-TM-X-53742, Marsh-Ill Space Flight Center, Huntsville, Alabama, June 1968.

11. "Quality Assurance, Guidance to Nondestructive Testing Techniques," Army Material Command, AD 728-162, April 1970, pp 148-152.

12. W. E. Gumm and J. E. Turner, "Nondestructive Testing Spectra," Chemical Engineering, Vol 83, No. 17, Aug. 16, 1976, pp 64-68.

13. L. A. McElwee and T. W. Scott, "Sonic Leak Detector," American Gas Journal, Aug. 1957, pp 14-17.

14. F. V. Long, "Sonic Leak Detection," Pipeline News, Aug. 1960, pp 18-22.

15. R. C. Quisenberry, "Leak Detection Technique Improvement Study for Space Vehicles," Final Report for Project NAS8-2563, Ohio University, Athens, Ohio, June 1963.

16. A. E. Wilson, "How--and with What-To Find Cable Faults," Telephony, Vol 188, No. 5, Feb. 1975, pp 38-45.

17. Anon. , "Ultrasonic Leak Detection," Tanker and Bulk Carrier, VO1 18, No. 4, Aug. 1971, pp 10-11.

18. N. Chretien, P. Bernard, and B. Barrachin, "Inspection of Steel Pressure Vessels by Acoustic fiission," International Conference on Pressure Vessel Technology, San Antonio, Texas, Oct. 1973.

19. A. N. Jette, M. S. Morris, J. C. Murphy, and J. G. Parker, "Active Acoustic Detection of Leaks in Underground Natural Gas Distribution Lines," Materials Evaluation,. Vol 35, No. 10, Oct. 1977, pp 90-96.

20. S. H. Bichard and L. M. Rogers, "A Review of Industrial Applications of Thermography," The British Journal of Nondestructive Testing, Vol 1S, No. 1, Jan. 1976, pp 2-11.

21. R. B. Aronson, "Heat Pictures Tell the Inside Story," Machine Design, Vol 48, No. 3, Feb. 12, 1976, pp 99-103.

22. J. M. Furan and F. M. Gryna, Jr., Quality Planning and Analysis, McGraw-Hill, Inc., 1970.

23. Sampling Procedures and Tables for Inspection by Attributes? MIL-STD-105D , Department of Defense, Government Printing Office, April, 1963.

APPENDIX G

BIBLIOGRAPHY

1. Anon. , "Method for Vacuum Leak Calibration, " Journal of Vacuum Science and Technology, Vol 5, No. 6, NOV. 1968.

2. Anon., "Audible Noise from Power Lines Measurement--Legislative Control and Human P.esponse," IEEE Transactions Power ADParatus Systems, Nov.-Dec. 1975, pp 2042-2048.

3. Anon., "Freon Injection Techniques for Saturn Systems Leak Check," NAS8-11910, Astro-Space Labs, lnc., Huntsville, Alabama.

4. Anon. , "Leak Testing of Air Conditioner Components," Metal Progress, Vol 106, No. 5, Oct. 1974, p 102.

5. I. G. Baryshnikova, et al., "Leak.Simulator for Calibrating Helium Leak Detectors During Tests by the Probe Method," Instruments Experimental Technology, Vol 16, No. 6, Nov.-Dee. 1973, pp 1763-1764.

6. A. J. Balterham, "Locating Condenser Tube Leaks Using the Foam Blanket Method," British Journal of Non-Destructive Testing, Vol 15, No. 4, July 1973, pp 108-111.

7. A. J. Bialous, "Characteristics and Sources of Commercially Available Leak Detectors," Final Report, General Electric Company for the National Aeronautics and Space Administration.

8. Guy E. Blachmar, "Find Leaks Faster with Ultrasonic Leak Detectors," Hydrocarbon Processing, Vol 52, No. 1, Jan. 1973, pp 73-74.

9. R. N. Bloomer, "The Vacuum Bubbler as a Non-Destructive Testing Technique," British Journal of Non-Destructive Testing, May 1974, pp 72-75.

10. Walton E. Briggs and Leo J. Blumle, "Frontiers of Leak Detection," Journal of Vacuum Science Technology, Vol 14, No. 1, Jan.-Feb. 1977.

11. S. Burman, "Scope of Welding Technology in the Manufacture of Vessels for Cyrogenic Semites," Indian Welding Journal, Vol 7, No. 2, May 1975.

12. E. O. Butts, "Detecting Leaks in Pipelines and Storage Tanks," Engineering Journal, Vol 60, No. 3, May-June 1977, pp 45-47.

13. Isaac Amerman and John Janus, "A Sonic Transducer to Detect Fluid Leaks," NASA-SP 5971(01), May 1975.

14.. "R. R. Cyr and D. W. Wathins, "Facepiece to Face Leakage Evaluation Using a Helium Leak Detector Method," Journal of Vacuum Science Technology, Vol 12, No. 1, Jan.-Feb. 1975, pp 419-422.

15• L. L. Dailey, "A New Chlorine Gas Detector," Instruments in the Aerospace Industries, Vol 21, 1975.

16. L. Wang Lau, "Data Analysis During Containment Leak Rate Test," Power Engineerin& VO1'78, No. 2, Feb. 1974, pp 46-49.

17. A. R. Davidson, "Leak Detection of Large Pressurized Spherical Balloons," #F19628-67-C-0414, Air Force Cambridge Research Laboratory, April 1968.

18. L.G. Davies, et al., "Leakage Through Cracks.in LNG Tankage," Final Report for Maritime Administration Contract No. 3-36301, May 1974.

19. "Design Criteria for Zero Leakage Connectors for Launch Vehicles—Advanced Leakage Tests," Vol. s.

20. W. Frederick, "Substation Insulator Failure Prevention by Ultrasonic Corona Detection," IEEE Transactions Industrial Applications, Vol 1A-8, No. 1, Jan.-Feb. 1972, pp 82-83.

21. M. Gaskel, et al., "Methods and Instruments for Measuring and Inspecting Petrochemical Equipment," Chemical and Petroleum Engineerin& Vol 10, No. 7-8, July 1974.

22. A. H. Getzel and C. Fairburn, "Study and Evaluation of Special Leak Test Inspection Equipment," Frankford Arsenal Project IEP-MIC-198, April 1959.

23. A. M. Grigoren and A. 1. Fursov, "Vacuum Gauge Lead Detectors," Instruments and Experimental Techniques, Vol 17, No. 6, Part Z, Nov.-Dee. 1974, pp 1740-1742.

24. A. P. Grossman, "Find Heat Exchanger Leakage Accurately," Hydrocarbon Processing, Vol 54, No. 1, Jan. 1975, pp 58-59.

25. R. T. Harrold, "Relationship Between Ultrasonic and Electrical Measurements of Under-Oil Corona Sources," IEEE Transactions Electrical Insulation, Vol EI-11, No. 1, March 1976, pp 8-11.

26. B. L. Johnston, "Ultrasonic Flowmeter Nucleus of Unique Leak Detection System," Pipeline Gas Journal, Vol 203, No. 12, Oct. 1976.

27. R. E. Koncen and A."Hafner, "Solid State Portable Gas Leak Detector," US Patent No. 3,187,558.

28. H. Kurose, "New Methods for Tank Leakage During Ship Construction," Shikawajima-Harima Engineering Review, Vol 12, No. 4, July 1972.

29. J. C. Maliakal and W. E. Briggs, "Advances in Leak Detection," Research and Development, May 1973, pp 45-50.

30. R. W. McClung, "ASTM Nondestructive Testing Standards Program," Nondestructive Testing Standards—A Review, 2977, pp 3-11.

31. F. R. McLean, "Testing Underground Flammable Liquid Tank Systems for Leakage," Fire Journal,. Vol 66, No. 6, Nov. 1972, pp 24-31.

32. L. .R. McMaster, "Sensor for Detecting Meteoroid Penetration of Pressurized Cells," NASA-TH-6447, Sept. 1971.

33.. "Military Standard—Indicators," Mil-Std-1211, June 1969.

34. B. C. Moore and R. E. Cumarillo, "Swept Helium Leak Detection," Journal of Vacuum Science and Technology, Vol 10, No. 2, March-April 1973, p 404.

35• 0. Nigol, "Location of Leaks in Gas-Filled Underground Cables," IEEE Power Applied Systems, Vol PAS-89, No. 7, Sept.-Ott. 1970, pp 1440-1443.

36. J. J. Obrzut, "Thermography Pinpoints Costly Heat Losses," Iron Age, Vol 219, No. 7, 1977, pp 57-59. "

37. W. O'Keefe, "Progress Report on Infrared Studies: What Aerial and Ground Services Are Doing," Power,. Vol 119, No. 5, May 1975, PP G4-6G0

38. B. S. Prahallada Rae, M. S. Murthy, and V. V. K. Rama Rae, "Helium Leak Detector," Indian Journal of Technology, Vol 10, No. 10, Oct. 1972, pP 385-387.

39. V. V. K. Rama Rao and B. S. Prahallada Rae, "Sniffing Attachment with Improved Response Time and Sensitivity," Vacuum, Vol. 25, No. 6, June 1975, pp 273-275.

40. A. W. Read and R. A. Umpleby, "Measurement of Air Leakage into Large Boilers by.Helium Tracer Injection," Combustion, Vol 44, No. 5, Nov. 1972, pp 13-16.

41. D. L. Robinson, "Acoustics Analysis Locates Defects in Buried Pipe," Metals Engineering Quarterly, Vol 15, No. Ii Feb. 1975, pp 17-21.

42. D. S. ROSS, "Unique Method of Leak-Rate Measurements," Journa? of Environmental Science, Vol 16, No. 3, May-June 1973, pp 27-32.

43. V. F. Rozal, "A Method of Calibrating Test Leaks," Soviet Journal of Non-Destructive Testing, Vol 12, No. 4, July-Aug. 1976, pp 459-460.

44. E. E. Seiler, "Method for Leakage Testing of Tanks," US Patent No. 3,399,574, Sept. 3, 1968.

45. V. E. Skarat, G. V. Karpov, and V. L. Talroze, "Detecting Leaks by Mass Spectrometry with Volatile Liquids Used as Tracers," Instrumentation and Experimental Techniques, Vol 18, No. 4, July-Aug. 1975, pp .1197-1198.

46. L. Verheyden, K. Klein, and C. Croue,"Measurement of Helium Leaks 10^{-5} Times Better Than the Sensitivity of a Mass Spectrometer Lealc Detector," Vacuum, VO1 21, No. 11, Nov. 1971, pp 545-549:

47. H. P. Vind, "Materials for Leak-Proofing Navy Oil Tankers," Naval Civil Engineering Laboratory, Port Hueneme, California, Technical Note N-1252, Dec. 1972.

48. W. C. Worthington, "New Developments in Trapless Leak Detection," Research/Development, VO1 27, No. ll, Nov. 1976, PP 53-60.

49. Y. N. Zhigalin, "Leak Tests on Large Vessels," Measurement Techniques, Aug. 1975, pp 1206-1208.

APPENDIX H

PATENT BIBLIOGRAPHY

1. US Patent No. 3,859,845, "Leak Detector," Assignee: United States of America, NASA.

2. US Patent No. 3,874,224, "Leak Detecting Apparatus," Assignee: Seek-a-Leak, Inc.

3. US Patent No. 3,904, 907, "Helium Resonance Lamp and a Leak Detection System Using the Lamp," Assignee: Unassigned.

4. US Patent No. 3,908,468, "Storage Tank Leak Detector," Assignee: Mitsubishi Jukogyo Kabushiki Kaisha.

5. US Patent No. 3,912,967, "Heater Temperature-Regulating Circuit for Sensor of Halogen Leak Detector,'' Assignee: General Electric Company.

6. US Patent No. 3,938,116, "Leak Detection Device," Assignee: Molson Companies, Ltd.

7. US Patent No. 3,938,519, "Medical Liquid Container with a Toggle Film Leak Tester and Method of Leak Testing with Same," Assignee: American Hospital Supply Corporation.

8. US Patent No. 3,939,695, "Apparatus for Detecting Leaks."

9. US Patent No. 3,940,020, "Leak Detection System and Method," Assignee: Gilbert & Baker Manufacturing Company.

10. us Patent No. 3,969,923, "Leak Detector," Assignee: Valcor Engineering Corporation.

11. US Patent No. 3,973,249, "Apparatus for Detecting Leakage froM Container and Method Therefor," Assignee: Toyo Aluminum K.K.

12. US Patent No. 3,974,680, "Pipeline Leak Detector," Assignee: Inspection Technology Development, Inc.

13. US Patent No. 3,975,945, "Apparatus for Testing Pipe for Leaks," Assignee: Service Equipment Design Company, Inc.

14. US Patent No. 3,978,709, "Detection of Leakage from Liquid-Transporting Pipeline," Assignee: CHISSO Corporation.

15. US Patent No. 3,987,662, "Fluid Leakage Detection Apparatus," Assignee: Nippon Kokan Kabushiki Kaisha.

16. US Patent No. 3,987,664, "Dry-Testing System for Detecting Leaks in Containers," Assignee: Applied Fluidics, Inc.

17. US Patent No. 3,988,920, "Method for Detecting a Leak in a Reaction Tube When Forming a IIIA-VB Compound," Assignee: Siemens Aktiengesellschaft.

18. US. Patent No. 3,991,360, "Sensor Assembly for a Halogen Gas Leak Detector," Assignee: General Electric Company.

19. us Patent No. 3,996,789, "Leak Detection," Assignee: Imperial Chemical Industries, Ltd.

20. US Patent No. 3,999,065, "Leak Detection System with Wire Probe," Assignee: Varian Associates.

21. US Patent No. 4,001,.764, "Acoustic Method for Detecting Leaks from Submerged Pipelines," Assignee: EXXON Production Research Company.

22. US Patent No. 4,012,944, "Electronic Fluid Pipeline Leak Detector and Method," Assignee: Shafer Valve Company.