PVP-Vol. 487, Aging Management and License Renewal
July 25 – 29, 2004, San Diego, California USA
PVP2004-2969

CERTIFICATION PROGRAM FOR ASSESSING THE MECHANICAL INTEGRITY OF PRESSURE VESSEL SYSTEMS

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas

Richard Biel
Stress Engineering Services, Inc.
Houston, Texas

ABSTRACT

Pressure vessels play an integral role in the operation of facilities such as refineries, chemical plants, power plants, both on land and offshore platforms. Consequently, with the increased need for profitable production cycles and pushing pressure systems to their limits, the potential for failures has increased. All of this takes place in an environment where shut-downs and losses of production are expensive. The likelihood for catastrophic failures is also increased, which carries the potential for major costs due to equipment failure, lawsuits, and danger to the public. For these reasons, the Pressure Vessel Certification Program was developed. The cornerstone of this program is technical application of design methods coupled with detailed inspection for assessing the present quality of the vessel. The framework for this effort is built upon careful inspection and readily-accessible documentation that can be used as reference material and integrated within a companies' risk analysis and safety programs.

The long-term element of this program involves regularly-scheduled inspections (e.g. every 3 years) to ensure that the vessel conditions do not change to the point where safe operation is no longer possible. The intent is of the Pressure Vessel Certification Program to ensure that the inspected vessels operate safely for their intended service conditions and intended design lives.

BACKGROUND

Since the early 1970s, Stress Engineering Services (SES) has been integrally involved in the design, analysis, testing, inspection, and monitoring of pressure vessels. Based upon requests from industry and using its experience, a Pressure Vessel Certification Program was developed and is discussed in this paper. The cornerstone of the program is technical application of design methods coupled with detailed inspection for assessing the present quality of the vessel. The framework for this effort is built on careful inspection and readily accessible documentation that can be used as reference material and integrated within companies' risk analysis and safety programs. With the aging infrastructure for vessels around the world, there is a significant demand for programs that seek to ensure the safe and reliable operation of pressure vessels and systems.

Another feature of the program is the ability to re-rate or de-rate a vessel. For vessels that do not possess the desired level of structural integrity for the anticipated service, a vessel de-rate may be in order. On the other hand, vessels possessing more than sufficient material properties and wall thicknesses may be qualified for a re-rate that would permit operating at higher pressure levels. With the emphasis on increased through-put and production, vessel re-rates are an attractive option for companies having well-designed and maintained systems.

The long-term element of this program involves regularly scheduled inspections (e.g. every 1, 3, or 5 years) to ensure that the vessel conditions do not change to the point where safe operation is no longer possible. The intent is of the Pressure Vessel Certification Program to ensure that the inspected vessels operate safely for their intended service conditions and design lives.

INTRODUCTION

One of the primary advantages in implementing the Pressure Vessel Certification Program is the detailed documentation that accompanies the process. Each part of the program is based upon a definite assessment need and results in documentation that tracks every portion of the certification process. This is a service to vessel owners that will complement their existing documentation and provide missing paperwork if necessary.

This summary document provides basic descriptions of the work involved in the Pressure Vessel Certification Program. The items below are the fundamental elements of the program.

- Jurisdictional assessments (e.g. codes, standards, company requirements)
- Documentation (e.g. paperwork, drawings, operational history)
- Material evaluation and inspection
- Design qualification (design calculations for static and cyclic service)
- Final documentation, forms, and certificate if appropriate

Figure 1 demonstrates graphically the certification process and how each of the above elements is related. This flow chart depicts the logical sequence of events that will be used in the Pressure Vessel Certification Program. **Figure 2** provides an exemplar Gantt chart

That shows a potential time frame for the project's activities on a typical vessel.

DETAILS OF CERTIFICATION REQUIREMENTS

The sections of this document that follow provide details on the specific areas of the Pressure Vessel Certification Program and the user inputs that are required.

This summary is not exhaustive. The person certifying each pressure vessel has the responsibility to modify the certification elements or add inspection, test, or calculation requirements as necessary to adequately describe and certify the pressure vessel being studied.

Not all vessels can be certified. Those pressure vessels that do meet the owner or user specifications or requirements will not be certified. In this case, the owner or user will be given the results of the efforts expended in attempting certification less, of course, the certification statement itself.

Jurisdictional and Corporate Requirements

The owner or user should supply any jurisdictional and corporate requirements that apply to the subject pressure vessel. For an example in Texas, there are no jurisdictional requirements for pressure vessels. However, the owner's organization (or insurance company) may need to have some assurance from a third party that his pressure vessels are adequate or fit for service.

Some owners maintain their pressure vessels using NB-23 National Board Inspection Code as a matter of policy. Fabricators that are authorized to apply the "R" stamp use this Code. If the owner or user requires this Code, SES will use an authorized fabricator to perform the needed repairs or alterations and do the nameplate stamping. SES acts as general contractor and provides drawings, calculations, and inspections as required.

Other owners maintain their pressure vessels using API-510, Pressure Vessel Inspection Code as a matter of policy. If the owner or user requires this Code, SES will use an API-510 Authorized Pressure Vessel Inspector to perform the needed inspection functions and do the nameplate stamping. SES acts as general contractor and provides pressure vessel engineering, drawings, calculations, and inspections as required.

User Specifications

The owner or user should supply the target pressure rating and cyclic data for each pressure vessel as needed using a format similar to the User Design Specification VIII-2. The User's Statement information may be gathered or calculated or both by an engineering firm using an interview of the owner or user followed by a signed acceptance of the owner or user. This step is critical, as the analyst cannot proceed to do the inspections and calculations in the blind.

It is the responsibility of the owner or user who wants a pressure vessel to be certified under the Pressure Vessel Certification Program to provide a User's Statement. This statement sets the requirements for the intended operating conditions and a basis for inspecting, testing, and certifying the vessel or vessels.

The User's Statement should include all of the loadings listed below as apply to the subject pressure vessel.

- Internal and external pressure
- Weight of vessel and normal contents
- External mechanical loads such as other vessels and piping
- Wind and seismic design loads
- Temperature conditions and corresponding piping thermal loads
- Cyclic loads and whether or not a fatigue analysis of the vessel shell has been done in the past
- Upset conditions

The User's Statement should also include whether or not a corrosion and/or erosion allowance has previously been provided or needs to be provided for the future and, if so, the amounts of thickness.

The User's Statement must also include whether or not the subject pressure vessel has contained fluids of such a nature that a very small amount mixed or unmixed with air is dangerous to life when inhaled, or if the pressure vessel has ever been used in lethal service.

Drawings

The owner or user should supply the pressure vessel drawings as well as all the available history of inspections and repairs. If there is data missing or it is insufficient, suitable drawings will have to be made. Copies of the original drawings will be marked up with current inspection report results or new drawings will be made reflecting the current condition of the pressure vessel and the results of the metallurgical evaluations.

NONDESTRUCTIVE EVALUATION

SES uses an inspection methodology similar to that of API-572 and will use inspection forms developed specifically for this process. The findings in the inspection reports will be used as inputs to the calculations for pressure/temperature rating.

METALLURGICAL EVALUATION

The metallurgical evaluation associated with the Pressure Vessel Certification Program involves field metallurgical replication, positive material identification (PMI), and hardness testing. Other tests and inspections will have to be made on an individual basis.

Field Metallurgical Replication

Field metallurgical replication assessments are performed using portable equipment to reveal the materials microstructures. Metallurgical replication is an ASTM recognized technique that permits an in-situ, non-destructive examination of the component. The metallurgical replica can be examined on-site or at a metallurgical laboratory. A two-dimensional view, usually a planar view of the vessel shell, is observable on the replica. The image shown in **Figure 3** is a metallurgical replica showing the cellulose acetate film on a glass slide, where the area of interest is in the center.

Typical metallurgical information that is extracted from a replica includes present metallurgical condition of the area that is examined, fabrication and thermal processing history, verification of a rolling direction of plate product, grain size determination, phase identification and verification of cast and forged structures. Replicas can also reveal the presence of carburization by identifying the extent of carbides or thermal degradation within the matrix. A typical photomicrograph from a metallurgical replica is shown in **Figure 4**.

Metallurgical replication is commonly used to assess surface-breaking or near-surface surface indications or flaws that have been identified by acoustic emission testing or other non-destructive examination techniques. Furthermore, it allows an examination of potentially damaged or previously repaired regions as identified by a review of the vessels inspection or repair history.

Positive Material Identification

Positive material identification involves alloy determination using a portable alloy analyzer. Common analyzers are X-ray fluorescence models and optical emission spectrometers. The former provides a nearest alloy match to internal data bank of alloys and the latter having the capacity to detect carbon and provide an alloy match. SES uses qualified service companies for this service task.

Hardness Survey

A hardness survey is performed using portable hardness testers to measure the materials strength based on converted hardness values to ultimate tensile strengths. Instruments that sample the material in bulk (i.e. a Brinell indenter) versus instruments that measure hardness using microindentors are widely available and provided by SES. Hardness tests can be performed with minimal surface preparation to areas having a micro-polished and etched surface, such as in areas where hardness values are required along heat affected zones, welds or parent metals as shown in **Figure 5**. Hardness determination on areas with bulges and regions affected by fires or continuous elevated temperature exposure are commonly provided in comparison to remote and unaffected areas for comparison. **Figure 5** shows a microhardness survey indicated by the series of impressions in the parent metal, the heat affected zones and weld on a micropolished and etched area.

CALCULATIONS

Engineering calculations play an integral role in the design of any pressure vessel. Along the same lines, calculations should be performed as part of a pressure vessel certification process to ensure adequacy of design and that the vessel can withstand the anticipated loading. This effort involves analyses to address both static and cyclic loading.

Calculations for Static Loads

Using the measured thickness and other geometrical features as shown on the “updated” pressure vessel drawings, the calculations are done in two parts. PART ONE of the stress calculations is done using first principles for pressure, gravity and other static loads. This may include seismic calculations using base shear methods. The calculations would include at a minimum the following for all vessels:

- ***Internal pressure*** - Lame hoop stress at ID and OD or membrane hoop stress using Barlow’s equation (Pr/t) or both as needed.
- ***External pressure*** – Allowed external pressure calculated by ASME VIII-1.
- ***Nozzle loads*** – Pressure vessel stresses due to external loads using WRC-107.
- ***MDMT*** – Minimum Design Metal Temperature calculated by ASME VIII-1.
- ***For towers*** – Axial stress due to overturning moments from wind loads using ASCE –7, current version.

These calculations are a mandatory “sanity check” and are done for all pressure vessels regardless of any other Code requirements.

PART TWO of the calculations is used to demonstrate compliance with a specific construction Code, whether a vessel was originally built using a construction Code as a basis or not. If there are no jurisdictional or corporate requirements that direct the calculations to conform to a particular Code, the ASME VIII, Code, Division 1, 2, or 3 is to be used to determine the MAWP – Maximum Allowable Working Pressure at a specific temperature (VIII-1) or Design Pressure at a specific temperature (VIII-2 and VIII-3). All applicable Code calculations are to be done. While it is never possible to “Code Stamp” a used vessel with an ASME “U,” “U2,” or “U3” stamp, SES believes that the owner or user should have the Code calculations as a basis for comparison even if the pressure vessel does not conform to the Code.

If the pressure vessel requires special calculations, SES will use the methods of API-579 for crack-like flaws or non-crack-like flaws. The methods of limit analysis will be used as needed to “cut to the chase” using elastic-plastic methods.

Calculations for Cyclic Loading

Unlike calculations for static loading that are always required, calculations for cyclic loading are only performed when the operation of the vessel involves dynamics loads. Using the results of the static calculations as a starting point, methods such as those from API-579 or ASME Code (VIII-3) for cyclic calculations are used.

ACOUSTIC EMISSION

Acoustic emission (AE) is a viable NDT method for monitoring these vessels during either an on-line over-pressurization or during a proof test following repairs or modifications. Safety is typically a key issue in the program as a whole and for the test in particular. For these reasons, AE is often selected to provide real-time monitoring of the test. In terms of sensitivity, the ability to detect cracks is a combined effect of loading combination and flaw orientation. The target threshold is stress intensities that generate stresses at or above 65 percent of the yield strength. In terms of accuracy, a rule of thumb is that detections can be made within 10 percent of the distance between sensors. In other words, if sensors are placed 20 feet apart, detection can be made within a 2-foot window.

AE relies on high frequency sound (150 kHz) generated by “crack-like” discontinuities during changes in the stress field. **Figure 6** shows a screen capture shot of the software used to process the AE data. The main region of the figure shows a spherical vessel with marks showing crack-like activities. The other graphs show variables plotted against each other to determine the sources of crack excitation. **Figure 7** shows a wave guide that is the AE sensor mounted directly to vessels.

Testing Objectives

Acoustic emission testing is conducted during pressure or cool-down tests as a part of a certification inspection program. Provided below are several examples of how this testing works for specific vessel applications.

Testing Example #1. Monitor the entire regenerator vessel during an on-line over-pressurization prior to the shutdown to detect and locate active and significant discontinuities, which could be inspected at a later date via conventional NDT methods. This test is to be carried out to a minimum pressure level of 110% of the maximum pressure seen by the pressure vessel over the previous 12 months.

Testing Example #2. Monitor the entire vessel during the hydrostatic or pneumatic proof test to detect and locate active discontinuities. This test is to be carried-out to the old or new proof test pressure, as indicated by the applicable design code calculations. Furthermore, AE will provide an added level of safety since any crack propagation during the pressurization will be detected, prompting halting of the test to allow for further investigation of the source, before the proof test is to continue.

Provided below is an example list of characteristics of the AE procedure as applied to a specific vessel.

- The on-line over-pressurization inspection has the advantage of allowing a fairly accurate global inspection with the vessel under load, providing a picture of the current mechanical integrity of the pressure vessel. The sensitivity level is optimum if the background noise levels (process related) are not present. It provides a map of current active defect locations for further inspection, sizing, repair, etc. during the shutdown.
- The hydrostatic or pneumatic pressurization during an outage has a much higher sensitivity level due to the higher pressures (higher Hoop Stress levels) and also absence of process related background noise.
- The hydrostatic or pneumatic proof test is executed with the aid of two redundant calibrated pressure gauges, connected to the vessel via hard conduits, and mounted inside the AE field trailer, for continuous pressure monitoring. Alternatively, a pressure transducer can also be used in order to overlap pressure levels with test time and AE data for a much more accurate correlation.
- Typically, the hydrostatic or pneumatic test is executed with heated fluids, bringing the shell metal temperature to a minimum wall temperature level, to minimize the risks of brittle fracture. Skin thermocouples can also be attached to the vessel's walls for continuous temperature monitoring.
- For safety reasons, the immediate area surrounding the pressure vessel is barricaded for the duration of the pneumatic pressurization according to the requirements of the Field Safe Work Permit.
- Data analysis is performed at each pressure step, and if no active signals are detected, the pressurization sequence is allowed to proceed. Should indications of active discontinuities be detected, an immediate ultrasonic inspection is required at the source to verify and size the indication. Ideally, a Fracture Assessment Diagram-FAD should be prepared in advance for immediate evaluation of each discontinuity, based on accepted standards, such as API 579.

The entire AE inspection procedure is based on the 1998 ASME Boiler & Pressure Vessel Code, Section V, Article 12, *Acoustic Emission examination of metallic vessels during pressure testing*. Certification of personnel is based upon procedures specified by the American Society of Nondestructive Testing in ASNT-TC-1A and includes Level I, II, and III levels of certifications.

FINAL DOCUMENTATION

Once the engineer certifying the pressure vessel gathers all the necessary information and assesses the results of the tests performed on the pressure vessel, the information is the entered into a form similar to the API-510 versions. Sample alteration and inspection forms are provided in **Figure 8** and **Figure 9**, respectively. The figures are provided to show the type of information that is integrated into the Pressure Vessel Certification Program.

If the engineer finds that the pressure vessel meets the User's Statement requirements, then that engineer executes a signed and sealed certificate and provides it and the background data to the owner or user. If the engineer finds that the pressure vessel does not meet the User's Statement requirements, then the engineer and provides the background data to the owner or user along with a rationale for not certifying the pressure vessel.

CLOSING COMMENTS

Favorable feedback from industry has been received for the development of the Pressure Vessel Certification program. In addition to ensuring the safe and reliable operation of pressure vessels, the potential for re-rating existing vessels offers to industry the potential for increased throughput using existing equipment and systems.

REFERENCES

1. API 510, *Pressure Vessel Inspection Code - Maintenance Inspection, Rating, Repair, and Alteration*, Seventh Edition, American Petroleum Institute, Washington, D.C., 1992.

2. API 579, *Recommended Practice for Fitness-For-Service and Continued Operation of Equipment*, Washington, D.C., First Edition, January 2000.

3. *ASME Boiler & Pressure Vessel Code, Section VIII. Division 1*, 2001 edition.

4. *ASME Boiler & Pressure Vessel Code, Section VIII. Division 2 - Alternative Rules*, 2001 edition.

5. ASME HPS-2003, *High Pressure Systems*, Published by the American Society of Mechanical Engineers, New York, Date of Issuance: June 18, 2003.

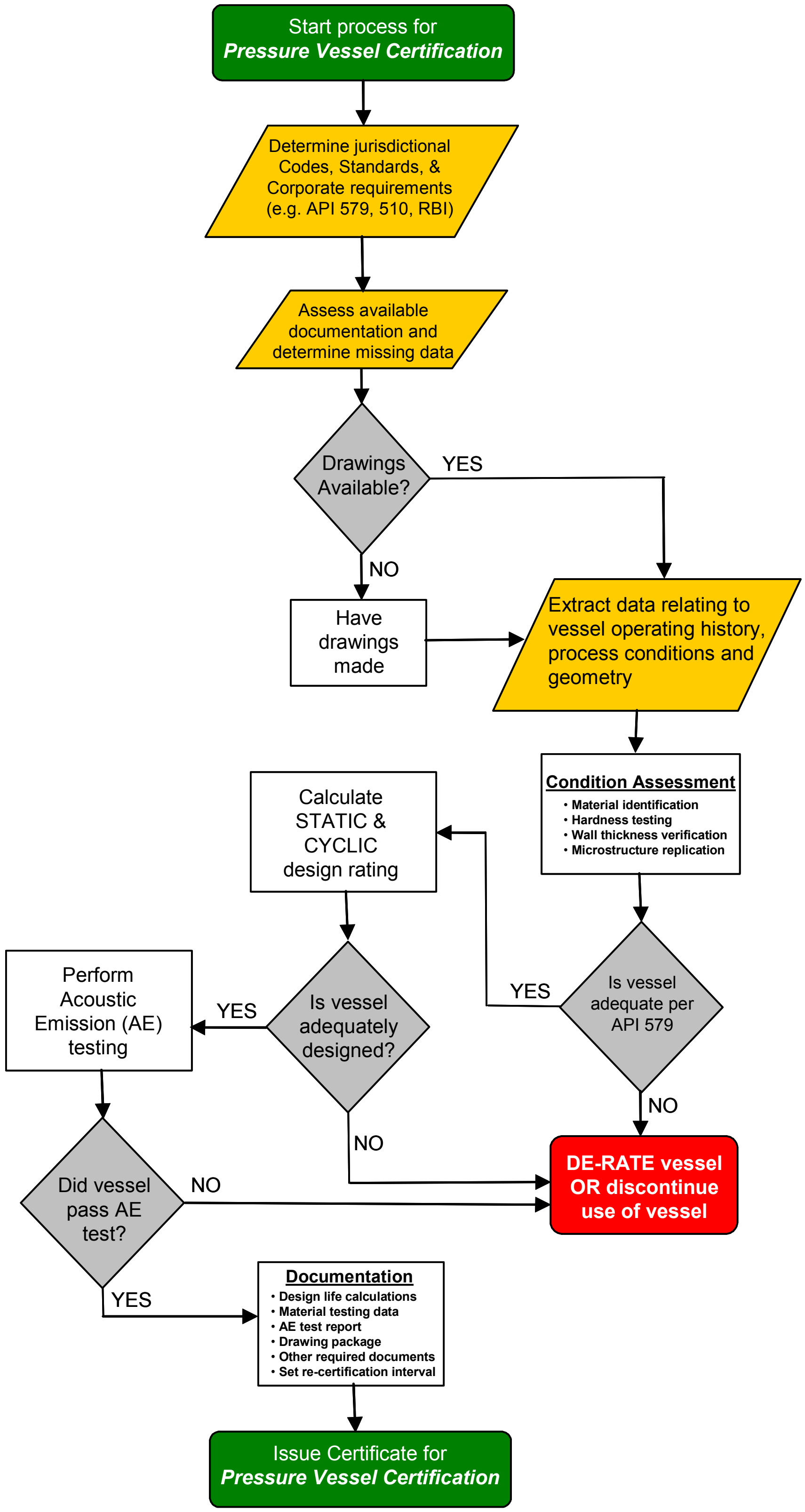

Figure 1 – Flow chart for the Pressure Vessel Certification Program

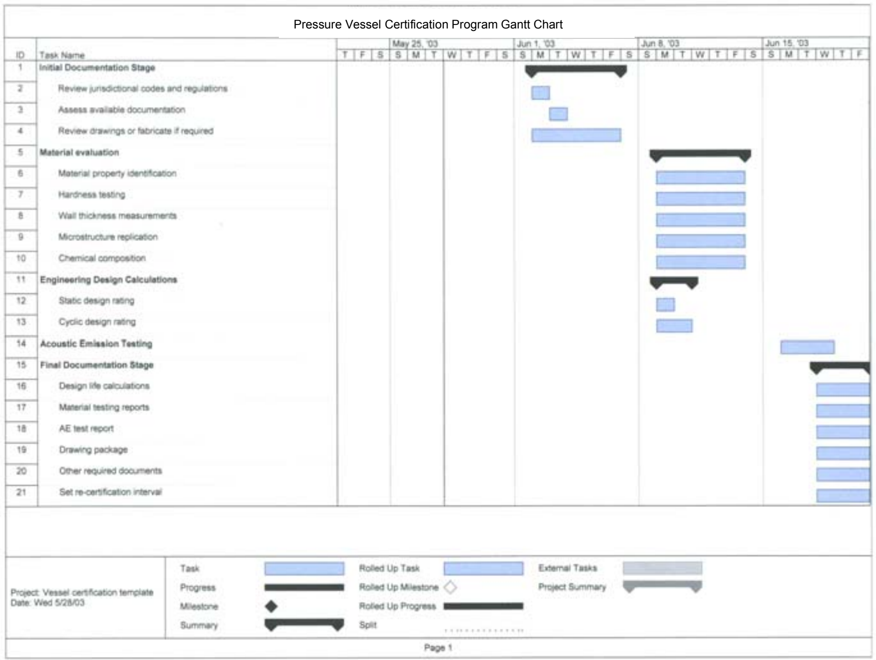

Figure 2 – Exemplar Gantt Chart showing schedule of activities

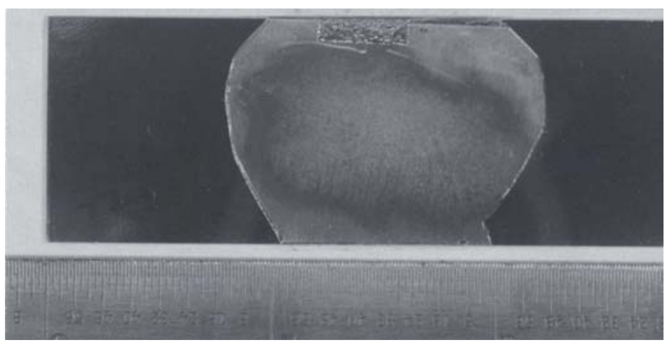

Figure 3 - A typical image of a metallurgical replica

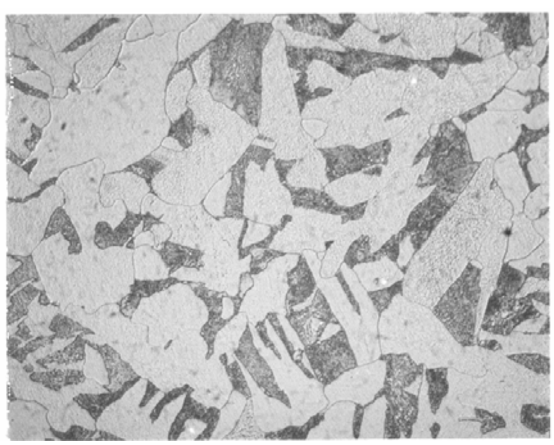

Figure 4 - Carbon steel microstructure observed on a metallurgical replica.

Figure 5 - Microhardness survey shown by the series of impressions

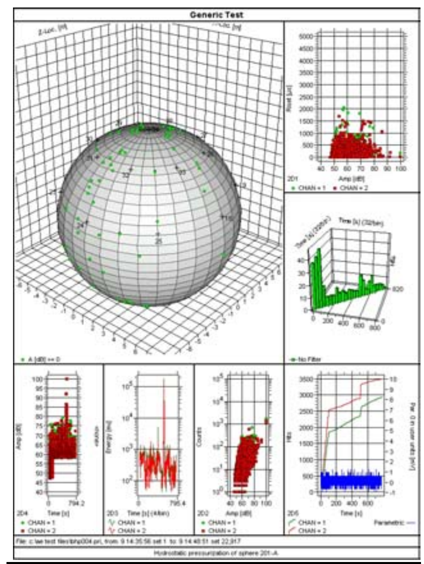

Figure 6 – Screen capture from AE processing software

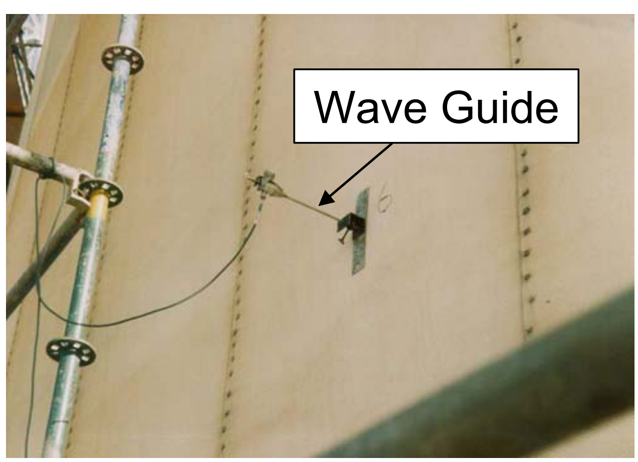

Figure 7 – AE waveguide attached to tank

SAMPLE ALTERATION OR RERATING OF PRESSURE VESSEL FORM

FORM DATE ______
FORM NO. ______
OWNER OR USER ______
VESSEL NAME ______

1. ORIGINAL VESSEL IDENTIFICATION ______
2. ORIGINAL VESSEL LOCATION ______
3. MANUFACTURER ______ SERIAL NO. ______
4. DESIGN TEMPERATURE ______ YEAR BUILT ______
5. TEST PRESSURE ______ POSITION ______
6. MATERIAL ______
7. SHELL THICKNESS ______ HEAD THICKNESS ______
8. PROPOSED VESSEL IDENTIFICATION (NEW LOCATION) ______
9. PROPOSED NEW VESSEL LOCATION ______
10. WORK ON VESSEL CLASSIFIED AS: ○ ALTERATION ○ RERATING
11. MANUFACTURER PERFORMING WORK ______
12. ORDER NUMBER ______ DATE ______
13. DESIGN TEMPERATURE ______
14. MAXIMUM ALLOWABLE WORKING PRESSURE ______
15. TEST PRESSURE ______ POSITION ______
16. TYPE OF TEST OR INSPECTION PERFORMED:
    ○ RADIOGRAPHIC TEST ○ ULTRASONIC TEST
    ○ MAGNETIC PARTICLE ○ PENETRANT TEST
    ○ VISUAL
17. LIST WORK PERFORMED BY MANUFACTURER (ATTACH DRAWINGS, CALCULATIONS, AND OTHER PERTINENT DATA):
18. SEE ATTACHMENTS FOR ADDITIONAL DATA? ○ YES ○ NO
19. CONSTRUCTION CODE ______

STATEMENT OF COMPLIANCE

WE CERTIFY THAT THE STATEMENTS MADE IN THIS REPORT ARE CORRECT AND THAT ALL MATERIAL AND CONSTRUCTION FOR AND WORKMANSHIP OF THIS ○ ALTERATION ○ RERATING CONFORM TO THE REQUIREMENTS OF THE ______ EDITION OF API 510, *PRESSURE VESSEL INSPECTION CODE.*

______
(alteration or rerating organization)

SIGNED ______
(authorized representative)

DATE ______

STATEMENT OF INSPECTION

I, THE UNDERSIGNED, AN INSPECTOR EMPLOYED BY ______, HAVING INSPECTED THE WORK DESCRIBED ABOVE, STATE THAT TO THE BEST OF MY KNOWLEDGE, THE WORK HAS BEEN SATISFACTORILY COMPLETED IN ACCORDANCE WITH THE ______ EDITION OF API 510, *PRESSURE VESSEL INSPECTION CODE.*

SIGNED ______

DATE ______

Figure 8 – Sample alteration or re-rating form

SAMPLE PRESSURE VESSEL INSPECTION RECORD

FORM DATE ______
FORM NO. ______
OWNER OR USER ______
VESSEL NAME ______

DESCRIPTION

NAME OF PROCESS ______ OWNER OR USER NUMBER ______
LOCATION ______ JURISDICTION/NATIONAL BOARD NUMBER ______
INTERNAL DIAMETER ______ MANUFACTURER ______
TANGENT LENGTH/HEIGHT ______ MANUFACTURER'S SERIAL NO. ______
SHELL MATERIAL SPECIFICATION ______ DATE OF MANUFACTURE ______
HEAD MATERIAL SPECIFICATION ______ CONTRACTOR ______
INTERNAL MATERIALS ______ DRAWING NUMBERS ______
NOMINAL SHELL THICKNESS ______
NOMINAL HEAD THICKNESS ______ CONSTRUCTION CODE ______
DESIGN TEMPERATURE ______ JOINT EFFICIENCY ______
MAXIMUM ALLOWABLE WORKING PRESSURE ______ TYPE HEADS ______
TYPE JOINT ______
MAXIMUM TESTED PRESSURE ______ FLANGE CLASS ______
DESIGN PRESSURE ______ COUPLING CLASS ______
RELIEF VALVE SET PRESSURE ______ NUMBER OF MANWAYS ______
CONTENTS ______ WEIGHT ______
SPECIAL CONDITIONS ______

THICKNESS MEASUREMENTS

SKETCH OR LOCATION DESCRIPTION	LOCATION NUMBER	ORIGINAL THICKNESS	REQUIRED MINIMUM THICKNESS	DATE

COMMENTS (SEE NOTE 2) ______

METHOD ______
AUTHORIZED INSPECTOR ______

NOTES:
1. USE ADDITIONAL SHEETS, AS NECESSARY.
2. THE LOCATION THAT EACH COMMENT RELATES TO MUST BE DESCRIBED.

Figure 9 – Sample inspection form