The Equity Engineering Group, Inc.

Summary of AE Test Results of Refrigerated Ammonia Tank LF 661

Final Report

Haifa Chemicals Ltd.
Haifa Bay, Israel

April 9, 2015

Submitted to:
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Project Number: HAIFISHA-1401
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1 INTRODUCTION

Haifa Chemicals Ltd. (Haifa) contracted the Equity Engineering Group, Inc. (E^2G) to provide assistance with the Acoustic Emission Testing (AET) and evaluation of the refrigerated Ammonia Tank LF 661, the results of which are summarized in this report. E^2G had previously recommended an AET inspection approximately 10 years after the detailed Fitness for Service (FFS) assessment of the tank that was performed in 2005 (Reference 1). AET is widely recognized as the most reliable method for inspecting refrigerated ammonia storage tanks to detect the presence of ammonia stress corrosion cracking.

2 PRIMARY OBJECTIVES

The primary objective of E^2G's involvement was to assist Haifa Chemicals Ltd with the AET inspection and with the assessment of the suitability of LF 661 for continued service. In order to achieve these objectives, the following tasks were completed:

- Helped identify a highly qualified and experienced AET contractor to perform acoustic emission testing (AET) of the LF 661 while it was in service. Stress Engineering Services (SES) was among the short list of vendors recommended by E^2G and was eventually selected by Haifa Chemicals as the AET contractor. SES has extensive experience and knowledge in this specialized area and have AE tested more than 100 cryogenic tanks.
- Provided a schematic drawing of the LF 661 tank to help identify critical areas to be used for AET waveguide sensor locations.
- Assisted Haifa Chemicals with the development of requirements for the AET of LF 661 including recommendations on tank fill height before the test and during the test.
- Worked with SES to finalize global aspects of the AET procedure that was used.
- The author of this report, Jonathan Dobis, witnessed the AET of LF 661 in Haifa, Israel from the start of test to the completion of test.
- Reviewed the preliminary and final results of the AET while in Haifa, and the SES final report.

3 EXECUTIVE SUMMARY & CONCLUSIONS

3.1 The AET inspection was successfully completed on February 7, 2015 after filling to 12,000 metric tons of anhydrous ammonia which was approximately 105.6% of the maximum level that the tank was filled to during the prior seven months.

3.2 The results of the AET inspection did not reveal any significant evidence of crack-like indications affecting the structural integrity of the tanks walls, structural welds, internal attachments, nozzle attachments, and welds attaching circumferential stiffeners to the tank. No evidence of ammonia stress corrosion cracking or other crack-like defects was identified so follow-up inspection using other methods such as UT shear wave inspection was not required.

3.3 Based on the results of the 2015 AET inspection, and the minimum flaw size capable of being detected during the AET, the minimum remaining life of LF 661 is re-established as 55 years into the future from February 2015. This is based on an assumption of a conservative initial flaw size of 0.06 inches deep x 0.36 inches long which is the same flaw size that was used in the 2005 analysis and is well within the limits of detection of the AET technology used by SES for this inspection.

3.4 LF 661 continues to be among the best designed tanks E^2G has assessed. Tank LF 661 has a unique double concrete wall containment system, a highly effective release mitigation design, and certain shell design details that significantly lessen stresses at what are typically critical locations in a domed ammonia tank. These design details, coupled with very slow crack growth at operating conditions reduce the risk of SCC to very low levels. A water-curtain deluge system was installed in 2013 as additional method of risk mitigation; the deluge system is tested monthly.

4 RECOMMENDATIONS

4.1 Haifa Chemicals should continue to purchase ammonia with minimum of 0.2% water to help minimize the likelihood of ammonia stress corrosion cracking, the primary concern with refrigerated ammonia storage tanks. Consistent operation at refrigeration temperatures also helps minimize the likelihood of cracking.

4.2 The AET inspection should continue to be used as a means of primary inspection and should be repeated within 10 years to conform and validate these baseline results using the same procedure and the same waveguide locations.

4.3 In order to further enhance risk mitigation, the water-curtain deluge system and all other "safety belts" around the tank should be maintained and tested periodically.

5 ACOUSTIC EMISSION TEST PROCEDURE

A valid Acoustic Emission type 1 (over stress) test in accordance with ASTM E1930-7 was performed by restricting the fill height to 11,400 MT for six months prior to the test. When the test was executed, Haifa was required to fill the tank to its full capacity of 12,000 MT. Haifa and SES agreed upon certain hold points during the test fill. The fill chart supplied by Haifa indicated 11,400 MT was previously exceeded on or around June 10, 2014 so that the test date in February exceeded the requirements for a 6-month minimum run length prior to the 105% fill test.

SES installed 90 waveguide sensors around the perimeter of the LF 661 before the final fill and tested and calibrated each sensor before the start of the AET. Installation of the 90 sensors provided coverage of 100% of the weld seams of the tank. SES collected data around the clock from the beginning of the fill cycle on February 6, 2015 until February 7, 2015. E^2G was on site and or in contact with Haifa Chemicals and SES during the installation of the waveguides and throughout the 22-hr fill test, and reviewed the results with both parties following the completion of the test.

6 FOLLOW-UP INSPECTION

Haifa Chemicals was prepared to perform follow-up inspection in the event the AET identified indications during the test. However, the results of the AET test were "clean" and no follow-up ultrasonic inspection (UT) shear wave inspection was warranted or recommended. What this means is crack-like indications, if any, are below the limit of detection of all practical methods of crack inspection including the most advanced and sophisticated methods of ultrasonic inspection (UT), radiographic inspection (RT), etc.

7 THE ROLE OF EQUITY ENGINEERING IN THE AE TEST

The author of this report, Mr. Jonathan Dobis, P.E. of E^2G visited the Haifa Bay site during the test as an impartial third party witness to observe the test and to review the results. He did not play a direct role in the test execution. Test execution was handled directly between Haifa and SES. Mr. Dobis was present to consult with Haifa on the test procedure and the need, if any, for follow-up inspection.

8 REFERENCES

1. The Equity Engineering Group, Inc. FFS Assessment of the LF 661 Tank, February 2005.
2. SES Report on ACOUSTIC EMISSION MONITORING OF ONE 12,000 TONS CRYOGENIC ATMOSPHERIC AMMONIA STORAGE TANK (LF 661), DURING AN IN-SERVICE LOADING WITH PRODUCT, 16 March 2015.

STRESS ENGINEERING SERVICES INC.

an employee-owned company

ACOUSTIC EMISSION MONITORING OF ONE 12,000 TONS CRYOGENIC ATMOSPHERIC AMMONIA STORAGE TANK (LF 661), DURING AN IN-SERVICE LOADING WITH PRODUCT

Final Report

Prepared for:

Haifa Chemicals, Ltd.

Haifa, Israel

16 March 2015

SES Document No.: 1152513-AET-RP-02-01-TECHNICAL REPORT SUMMARY

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ACOUSTIC EMISSION MONITORING OF ONE 12,000 TONS CRYOGENIC ATMOSPHERIC AMMONIA STORAGE TANK (LF 661), DURING AN IN-SERVICE LOADING WITH PRODUCT

Final Report

SES Document No.: 1152513-AET-RP-02-01-TECHNICAL REPORT SUMMARY
16 March 2015

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Executive Summary

Stress Engineering Services, Inc. (SES) was contracted by Haifa Chemicals, Ltd. to perform an Acoustic Emission (AE) monitoring of Anhydrous Ammonia storage tank LF-661, during filling to 12,000 tons located at the HAIFA CHEMICALS PORT in Haifa, Israel. The main objective of this inspection was to evaluate the structural integrity of the tank's walls, structural welds, internal attachments, nozzle attachments, and welds attaching circumferential stiffeners to the tank by means of exposing the tank to loads greater than experienced during the previous 6 months of normal operation. This type of global inspection using AET followed the guidelines from ASTM E 1930-7. This inspection is typically performed with the purpose of detecting and possibly locating "crack-like" indications which could be related to potential damage mechanisms in the tank such as ammonia stress corrosion cracking and thermal fatigue.

On February 6, 2015 SES began monitoring the tank with an initial product level of 3.7m/2,457 tons. Fill from a specialized cargo ship was executed to a final level of approximately 12,000 tons concluding on February 7, 2015. See Figure 1 for tank product level graph. The final level attained was equivalent to 105.6% of the reported maximum level the tank has been exposed to during the six months prior to the test date. The minimum recommended liquid level/hydrostatic pressure for a successful AE test is 105% of the TANK'S maximum level, therefore this is being considered a valid external inspection, in lieu of an internal inspection. The tank was instrumented with 90 Vallen Systeme VS-150 AE sensors, coupled to the tank's walls using stainless steel waveguides. Please refer to Figures 2a/b/c/d/e for sensor distribution utilized to cover the tank's 10 courses and associated welds. This number of 90 sensors was determined according to the tank's design plans so as to cover 100% of the tank's weld seams.

The analysis of the recorded AE data produced the following conclusions and recommendations:

1) **Analysis of recorded AE data does not indicate the presence of "crack-like" indications in the tank's structural welds or internal components.** The inspection, therefore, approves the structural integrity of the tank's walls, structural welds, internal attachments, nozzle attachments, and welds attaching circumferential stiffeners to the tank. No defects affecting the integrity of the tank were found. Crack-like indications are defined as indications which are being recommended for follow-up NDT inspection. Follow-up NDT inspection (if recommended) are typically executed using complementary advanced methods such as TOFD and Phased Array Ultrasonic methods to confirm the nature and dimensions of the indications. This information is to be used in an engineering assessment using methodologies such as API 579.

2) As a general and standard recommendation, Haifa Chemicals is being recommended to consider repeating this AE inspection within the next 10 years. By repeating this AE inspection Haifa Chemicals will be able to compare the AE data collected during the current monitoring, with the

AE data to be recorded during the next inspection. This comparison will determine if there has been any degradation of the tank's structural integrity between these two inspections.

3) Should Haifa Chemicals decides to repeat this AE inspection, we recommend the same number of AE transducers to be installed at the exact same locations as the ones utilized in the present inspection, so a proper comparison can be executed.

Also, the inspection procedure should attempt to repeat the 6 months operating at a reduced fill level, prior to the fill to 12,000 tons, mirroring the procedure executed in the present inspection.

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1. Introduction

Stress Engineering Services, Inc. (SES) was contracted by Haifa Chemicals, Ltd. to perform an Acoustic Emission (AE) monitoring of Anhydrous Ammonia storage tank LF-661, during filling to 12,000 tons located at the HAIFA CHEMICALS PORT in Haifa, Israel. The main objective of this work was to evaluate the structural integrity of the tank's walls, internal weld attachments, nozzle attachments, and welds attaching circumferential stiffeners to the tank by means of exposing the tank to loads greater than experienced in normal operation. This type of global inspection using AET is typically performed with the purpose of detecting and possibly locating "crack-like" indications which could be related to potential damage mechanisms in the tank such as ammonia stress corrosion cracking and thermal fatigue. This type of global inspection using AET followed the guidelines from ASTM E 1930-7.

2. Acoustic Emission Basics

Acoustic Emission Testing (AET) relies on the detection of sound waves propagating along the surface of a structure under test. The sources of these sound waves originate from several different sources, usually under some kind of mechanical loading: crack initiation, crack tip yielding, crack propagation, phase transformations in the base material, mechanical noise such as friction, fretting, etc. The characteristics of these sound waves are then carefully looked at to determine whether or not the sound waves detected were produced from critical flaws in the structure under test. Because of the high levels of process noise in most production facilities, some level of filtering has to be done to the data to distinguish good data from bad data. For this reason, sufficient data analysis of the raw data is required.

Acoustic emission testing offers many advantages for large scale NDT testing because it can be carried out during normal operations without taking the equipment out of service. When properly instrumented, an entire structure (i.e. pressure vessel, storage sphere, process column) can be tested to provide a global assessment of its mechanical integrity and defects significantly affecting the integrity can be quickly discovered. Having multiple sensors properly arranged also provides the benefit of triangulation techniques which allow the source location of the sounds (discontinuities) to be identified, thereby narrowing the scope of follow-up inspections.

3. SES Experience

3.1 SES Engineering

Stress Engineering Services, Inc. was established in 1972 and serves the Petrochemical, Refining, Utility and Power Industries in the fields of Design, Testing and Analysis.

SES offers fitness-for-service and specialized NDT inspections of pressure vessels, piping, reactors and other equipment, according to API 510, API 653 and API 579 standards.

The process industry involves storage and processing of many hazardous materials. Failure of this equipment is unacceptable because of the potentially catastrophic consequences. With increasing regulatory requirements and aging equipment there is more emphasis on the reliability of this equipment. Acoustic Emission (AE) monitoring is playing an increasingly important role in the monitoring of this type of storage tank. SES personnel have conducted AE inspection on over 1200 pressure vessels, reactors, piping and tanks. Our experience goes back to 1988 with involvement in Monsanto's and DuPont's tank testing programs. Several tests were conducted on tanks in Louisiana, Texas and abroad. Some of our previous clients with Ammonia Cryogenic Storage tanks are:

- Sterling Chemicals, Texas City – Texas
- Ultrafertil, Sergipe, Brazil
- Novacor, Red Deer, Alberta – Canada
- Monsanto Pensacola, Florida

To avoid failure, defects must be detected before they reach the critical size with regard to leak or unstable crack growth. Once detected and located by AET, and after properly confirmed by complementary NDT methods, fracture (API-579, Failure Assessment Diagrams-FAD, etc.) can determine if the defects are significant or if they can be tolerated in a tank. AE is major tool in detecting active defects because of the significant time and expense savings of not having to enter the vessel for inspection. Advanced Ultrasonic examination (AUT) is typically used to follow up on the AE sources to determine the size of and map the defects.

AE testing is a global NDT method suitable for assessing the structural integrity of pressure vessels, tanks, reactors, piping and other components. Only active damaging mechanisms are detectable by AE, leaving old and stable fabrication type defects untouched. These defects are discovered in processes like FFS and RBB. Proper test procedures should be developed for each application since these discontinuities might be driven by Hoop, thermal or a combination of distinct stress fields.

3.2 Methods

The AE test method is designed to detect defects and damage in metal and composite equipment. Materials produce high frequency sound waves, acoustic emission, when deformed. The deformation is usually local, at a crack tip or corrosion, and occurs during loading or over stressing. These sound waves travel along the surface and in the equipment. The general procedure consist of subjecting the equipment to a controlled stressing sequence while monitoring with sensors that are sensitive to acoustic emission caused by stressed defects.

3.3 Preparation

The preparation and the information given for the preparation of the test mainly determine the success of an AE test. It is essential that the previous operating, maintenance and inspection history be provided to SES's personnel, including repairs, alterations, maximum pressures, liquid levels and temperatures. The equipment must be slightly over stressed to produce AE, therefore the previous stresses must be known.

3.3.1 Cryogenic Ammonia Storage Tanks - The Challenge

The inspection of cryogenic storage tanks poses an important challenge to facilities all over the world. Today's very competitive market, in addition to the economic pressures to keep maintenance costs at a minimum level, tend to conflict with the need to protect the environment and the workers, against potential accidents. Often, tanks must be inspected at a certain fixed interval, depending upon local, state and federal regulations. On a Cryogenic Storage Tank, external inspection is often difficult, if not impossible, due to ice formation, insulation, etc.

The complete removal of the tank from normal service would allow for a full weld inspection from the inside. However, Opening a cryogenic ammonia tank means some damage to the infrastructure of the tank because of the temperature difference (-33C to ambient) and the Oxygen level in the tank, both when it is open and at the first stages of operation. Moreover the high costs associated with emptying the tank, decontamination, alternate storage facilities, cleaning, down time, and others, often make these inspections cost prohibitive.

3.3.2 The Solution

Current regulations, such as API 650/653 allow users/operators to inspect these and other atmospheric storage tanks, by means of alternate NDT methods like Acoustic Emission Testing (AET). The entire tank wall (main plates and weld seams), can be inspected globally via one single fill operation monitored with AET transducers attached to the tank's wall.

To avoid transducer lift-off by ice formation on cryogenic tanks, special stainless steel waveguides are used to acoustically couple the transducer to the tank's wall (see figure 1). This approach provides for optimal contact at all times, with or without the presence of ice near the area. Additionally, this minimizes the need for insulation cutouts, requiring only a ¼" diameter hole through the insulation, which is easily reparable. Furthermore, the inspection is carried out with the tank in normal service. The test is pre-planned to include a controlled fill with the product from a pre-determined minimum level, to 105% of the tank's latest maximum level within the last 12 months. A typical 30,000 ton cryogenic ammonia storage tank (see fig.2) can be fully inspected with AET within a few days, without being taken out of service.

The results from the AET in-service inspection can indicate one of two possible scenarios: A-There are no significant flaws or discontinuities within the tank's wall, and the tank can continue to operate for another period of time (run). B- There is (are) significant flaw(s) or discontinuity (ies) which leads to the need for a follow-up inspection using alternate external NDT methods. These methods include manual and automated ultrasonic inspection and other conventional NDT techniques. These follow-up inspections (especially Automated Ultrasonic Testing) would be executed only at the areas pointed out by the AET monitoring, with the tank still in-service. In parallel to the follow-up inspection, it would be prudent to develop a Failure Assessment Diagram (FAD) for that particular tank to evaluate the significance of the discontinuities being confirmed and sized by the AUT inspection.

The FAD diagram is the last piece of information used worldwide; to support the decision making process of whether or not the discontinuity is significant enough to warrant a weld repair. In case the FAD study indicates the discontinuity is not critical enough for a repair, the tank can be maintained in service, and a monitoring program is implemented to follow the growth of the defect(s).

This approach allows management to properly plan ahead for future shutdowns, and potential repairs, if they will ever be needed. This entire approach described herein is commonly known as a Fitness-for Service (FFS) analysis. FFS analysis like this, has been applied all over the world to assess the safe continuing operation of pressure vessels, reactors, storage vessels, piping, aircraft, nuclear plants, offshore platforms, and structures in general.

Failure of an ammonia vessel is unacceptable because of the potential consequences of a gas release. Cracks caused by ammonia stress corrosion cracking (SCC) have been found in ammonia storage vessels. However, the existence of cracks does not mean that failure is imminent. With the possibility of failure in aging equipment, there is more emphasis on the reliability of this equipment.

Internal inspection is common practice, but can be less desirable, as opening the vessel can initiate or aggravate a SCC condition by admitting oxygen to the vessel.

AE has become a major inspection tool because of the time and expense savings of testing an entire structure in a short period of time without having to enter the vessel. SES's personnel has conducted AE on over 110 ammonia pressure vessels, piping and tanks including some of the largest ammonia storage tanks (30,000 tons) in North and South America.

SES's technique of installing the AE sensors requires the need of only one small diameter hole at each sensor location with basically no insulation removal. These small holes can be filled with spray foam after removal of the equipment.

For double wall ammonia storage tanks, SES uses a custom-built waveguide device that has been used successfully on these types of tanks. This device allows for testing the inside tank when the wall space between the inner and outer tanks is up to three feet apart.

4. Test Results

The acoustic emission monitoring of LF 661 produced approximately 10,000 data sets during the 24 hours of data acquisition. A total of ninety (90) AE transducers were utilized to cover the tank. This number of 90 sensors was determined according to the tank's design plans so as to cover 100% of the tank's weld seams.

The AE sensors were coupled to the tank by means SS wave guides and Silicon grease. The cylindrical shell of the tank was covered with five rows of eighteen AET sensors each. Please refer to Figures 2a b/c/d for the sensor distribution utilized on this inspection.

Prior to the start of data acquisition, the system was calibrated and the accuracy of the planar location algorithm was verified with good results. No coaxial cables had to be replaced as a result of this pre-test check. This "calibration" and sensitivity check was repeated at the end of the monitoring period, with good results.

Analysis of recorded AE data does not indicate the presence of significant "crack-like" indications in the tanks structural welds. Significant "crack-like" indications are defined as indications which are being recommended for follow-up NDT inspection due to their strong signals. These are typically executed using complementary advanced methods such as TOFD and Phased Array to confirm the nature and dimensions of the indications, which is to be used for an engineering assessment using methodologies such as API 579.

According to these results the global assessment of the mechanical integrity of the tank was found to be acceptable, with no known defects affecting the integrity of the tank.

4.1 Post Test Analysis

The criteria utilized to evaluate the AE data from LF661 was based on verifying the presence of the following characteristics and trends in the data set:

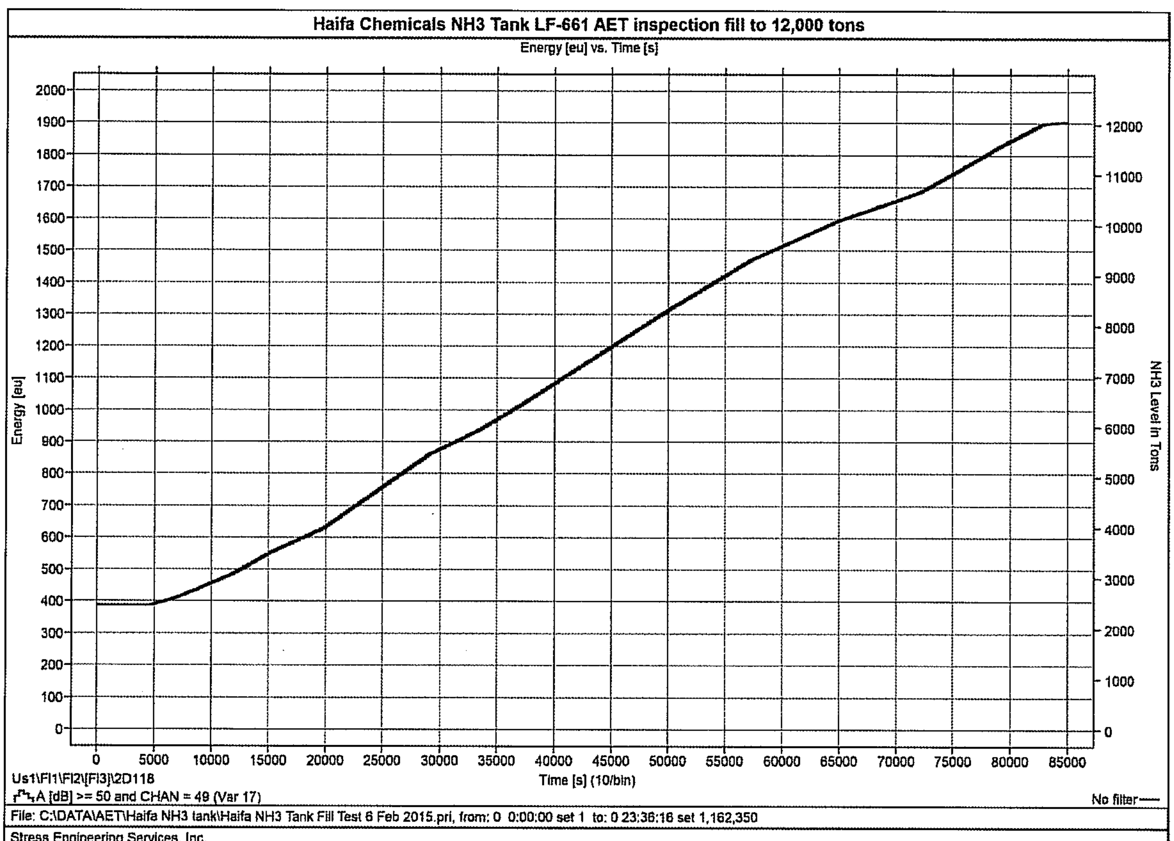
- Counts x Amplitude correlation indicating that the AE signals were originated from the release of high energy bursts within the metal itself. These are distinct from the correlation and trends resulting from noise generated during pumping, mechanical noise or electromagnetic interference.

- An increase (preferably exponential) on most of the AE attributes as the Hoop stresses increase due to increasing internal pressure. This is indicative of stresses that ultimately activate the existing discontinuities.

- Hits during holds. AE activity during steady pressure levels indicates possibly continuing release of AE energy even if pressure is being held constant. This is an indication of active flaws.

- Frequency distribution, rise-time distribution and energy levels typically found on crack-like indications.-

- Location graphs displaying clusters of AE events, both from planar and linear algorithms.



Vallen VisualAE™ by Vallen Systeme GmbH is licensed to Stress Engineering Services Inc., Houston, Texas, USA

Figure 1: Tank Level indicated as curve in blue during the 22 hours of monitoring

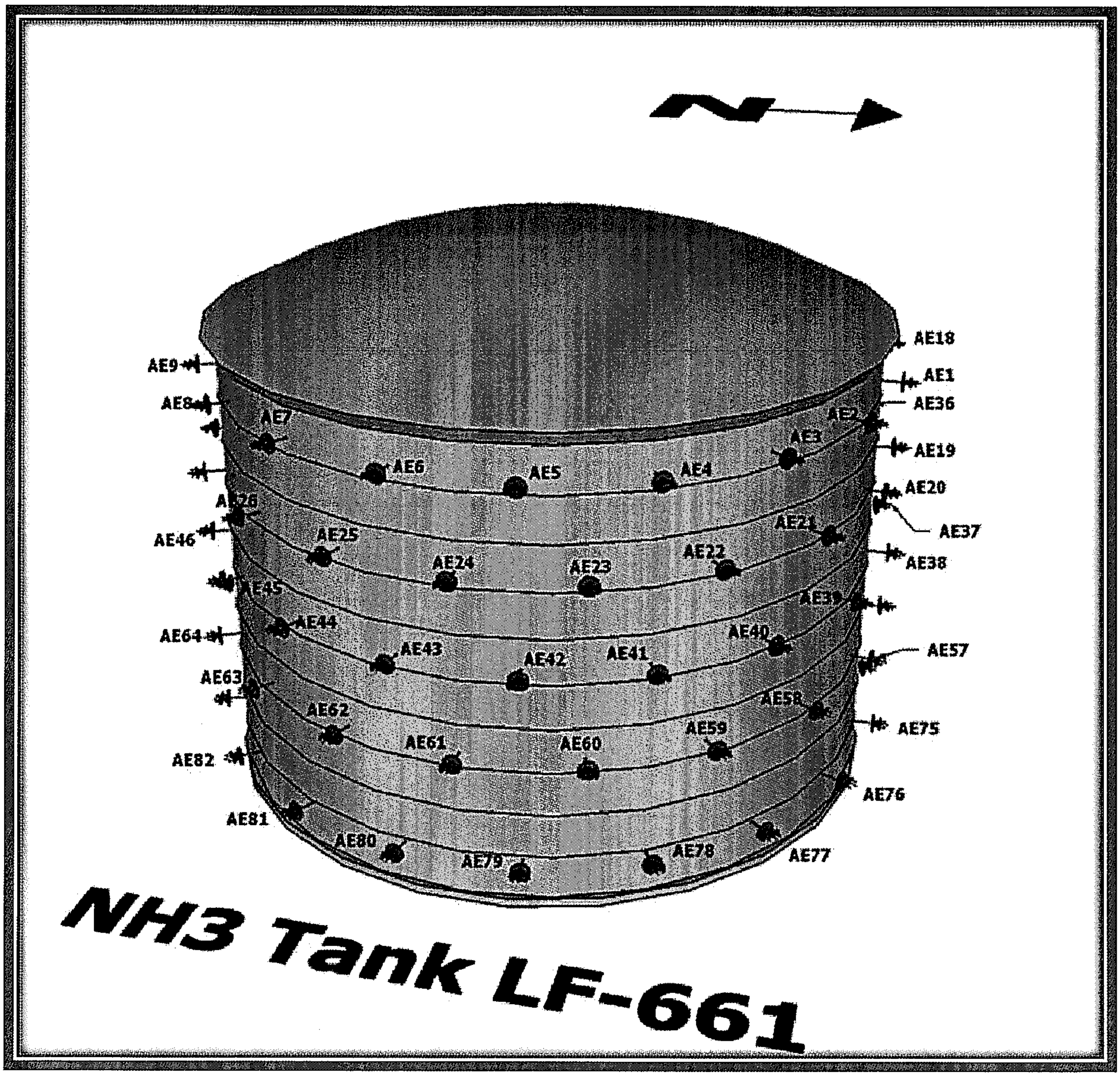


Figure 2a: AE Sensor Layout

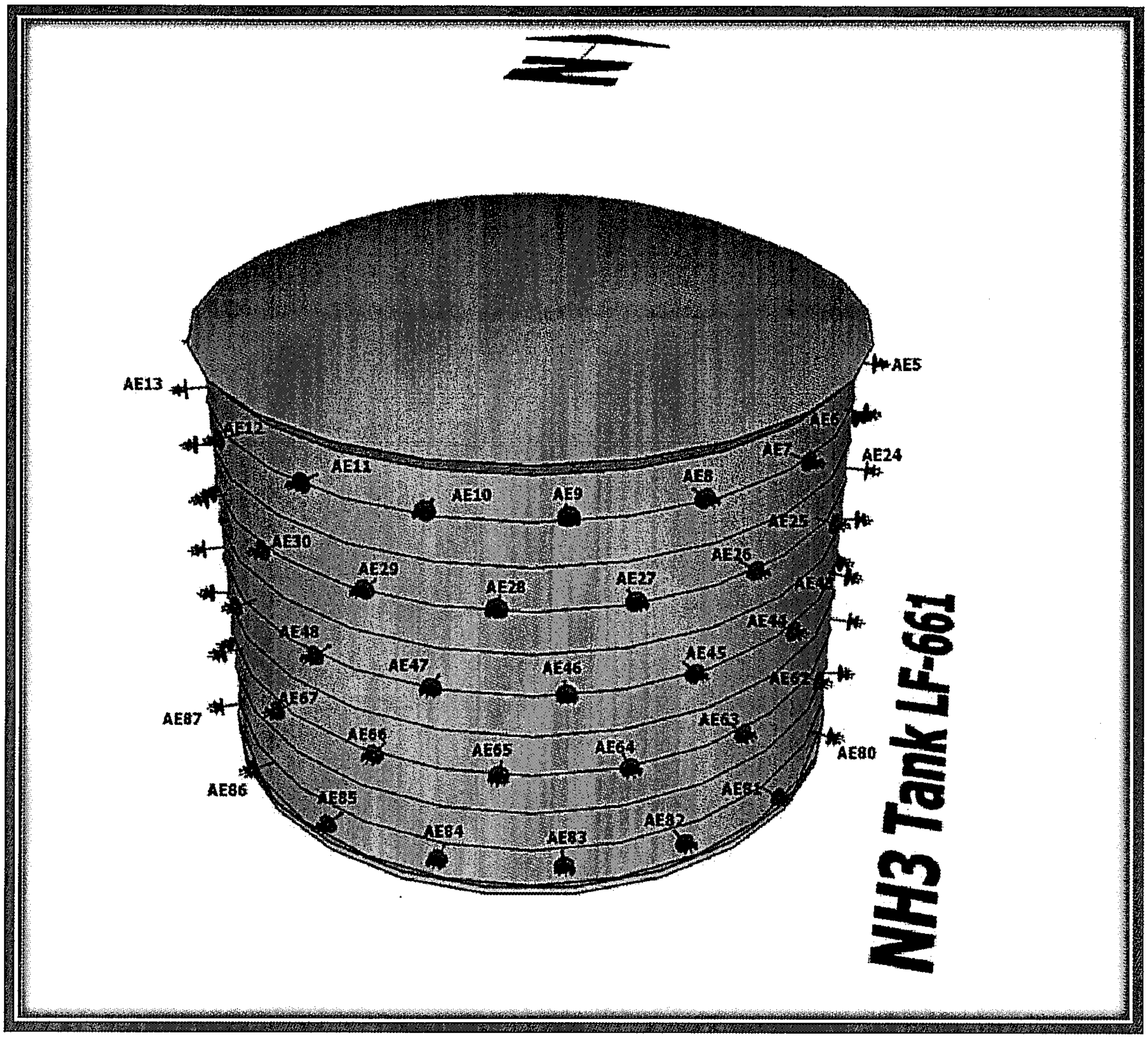


Figure 2b: AE Sensor Layout

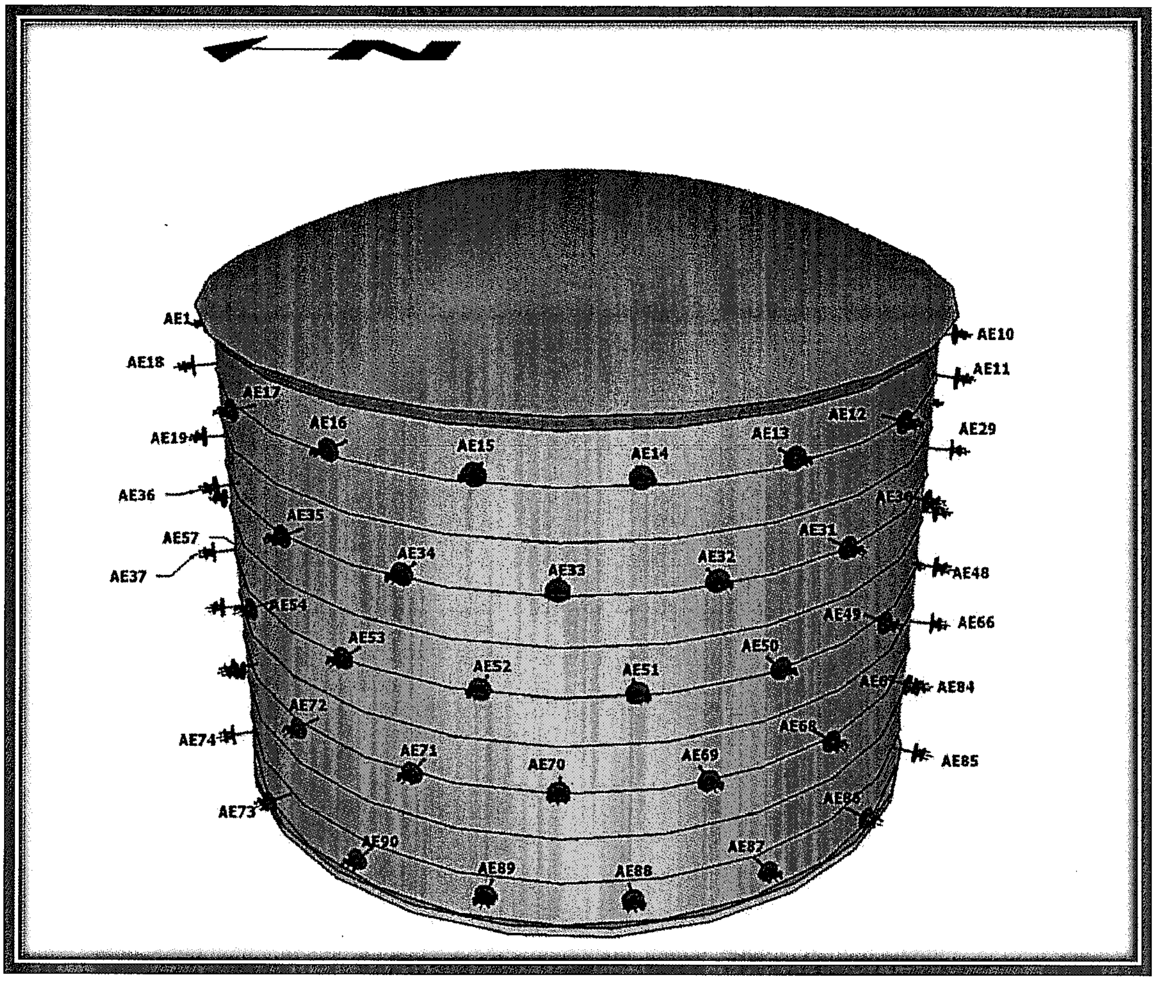


Figure 2c: AE Sensor Layout

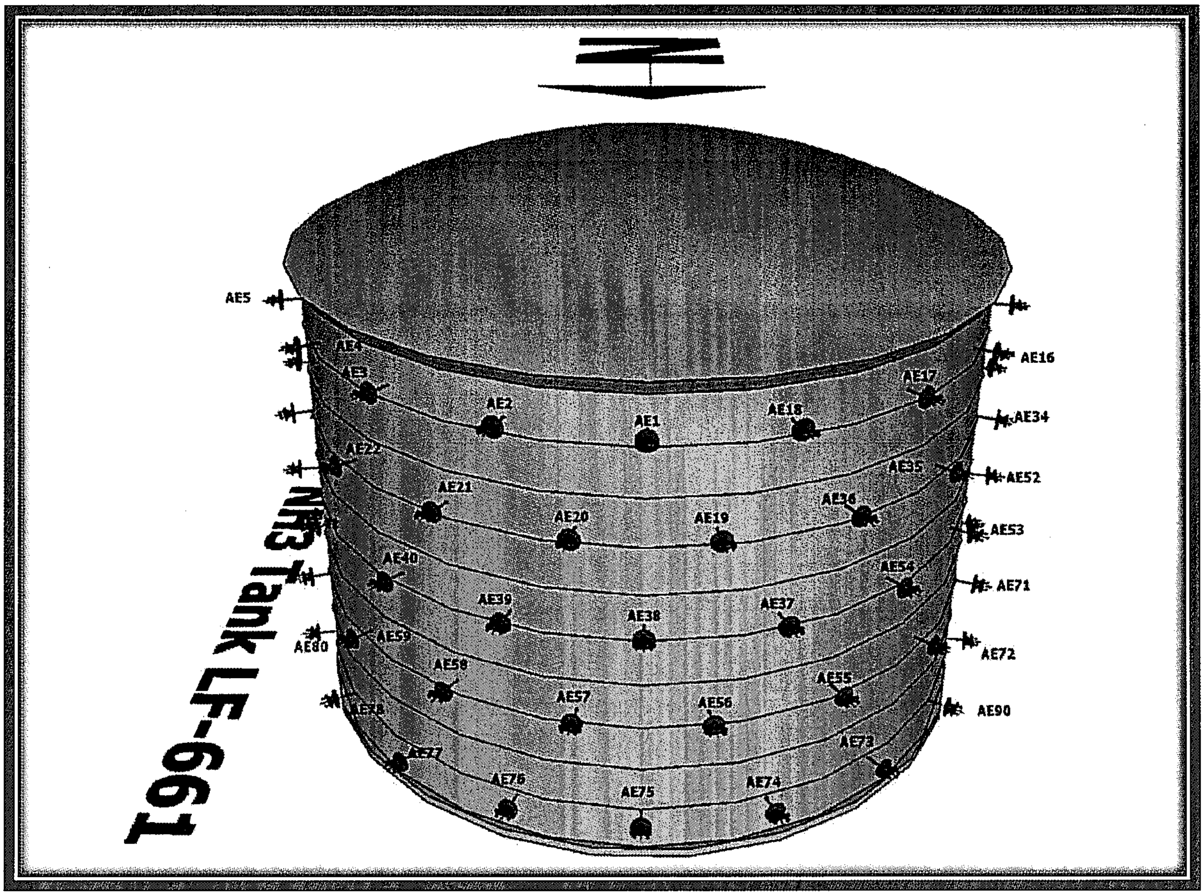


Figure 2d: AE Sensor Layout

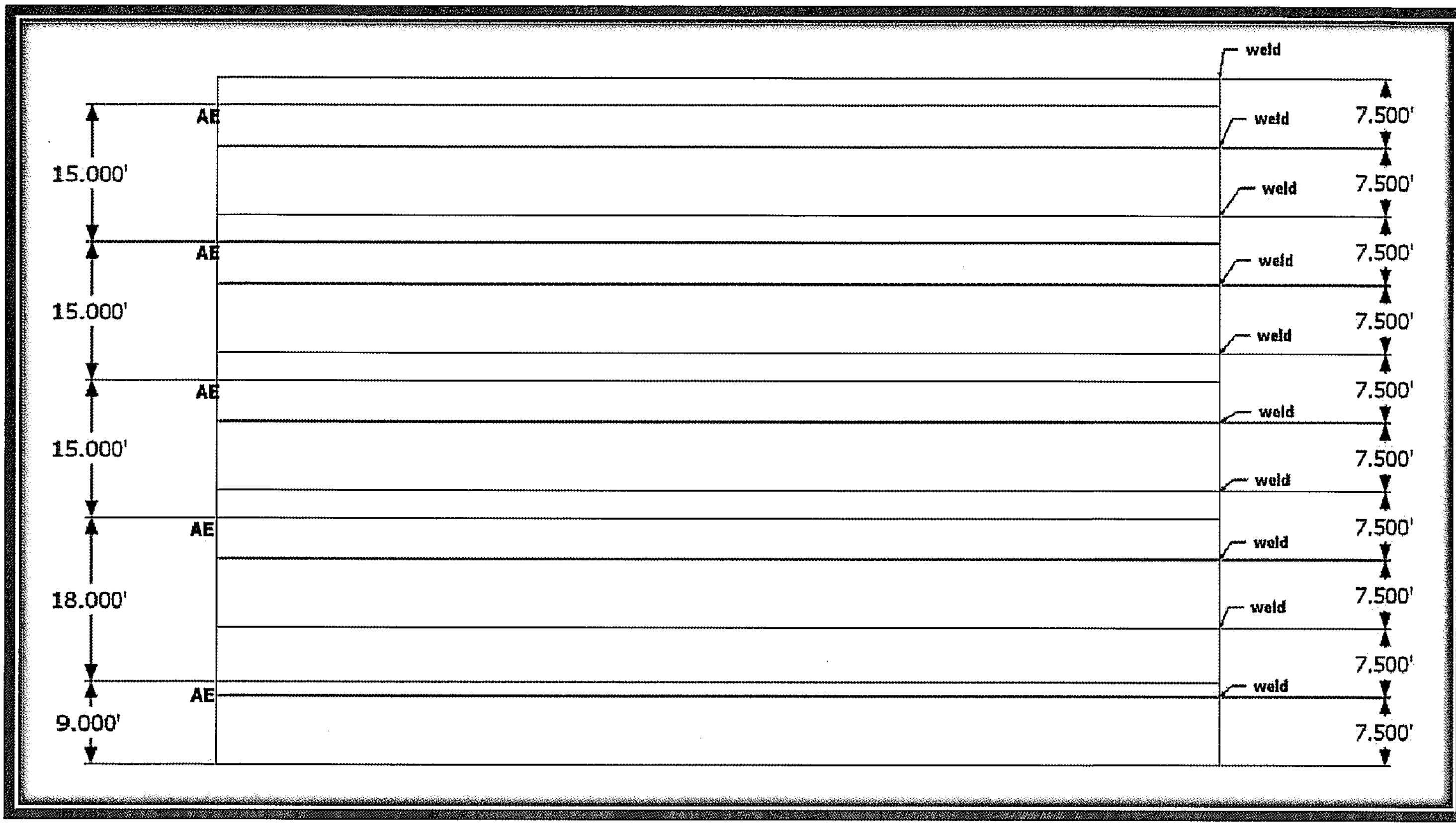


Figure 2e: AE Sensor Layout and circumferential weld elevations

5. Conclusion

On February 6, 2015 SES began monitoring the tank with an initial product level of 3.7m/2,457 tons. Fill from a specialized cargo ship was executed to a final level of approximately 12,000 tons concluding on February 7, 2015. See Figure 1 for tank product level graph. The final level attained was equivalent to 105.6% of the reported maximum level the tank has been exposed to during the six months prior to the test date. The minimum recommended liquid level/hydrostatic pressure for a successful AE test is 105% of the maximum level. The tank was instrumented with 90 Vallen Systeme VS-150 AE sensors, coupled to the tank's walls using stainless steel waveguides. Please refer to Figures 2a/b/c/d/e for sensor distribution utilized to cover the tank's 10 courses and associated welds.

> **Analysis of recorded AE data does not indicate the presence of "crack-like" indications in the tank's structural welds or internal components.** The inspection, Therefore, approves the structural integrity of the tank's walls, structural welds, internal attachments, nozzle attachments, and welds attaching circumferential stiffeners to the tank. No defects affecting the integrity of the tank were found.

Crack-like indications are defined as indications which are being recommended for follow-up NDT inspection. Follow-up NDT inspection (if recommended) are typically executed using complementary advanced methods such as TOFD and Phased Array Ultrasonic methods to confirm the nature and dimensions of the indications. This information is to be used in an engineering assessment using methodologies such as API 579.

6. Recommendations

Based on the analysis of the recorded AE data, SES recommends that HAIFA CHEMICALS considers the following actions:

- Consider this AE monitoring as a baseline and file the results of the present monitoring as a "non-invasive" global assessment of LF-661, in lieu of an internal inspection.
- Haifa Chemicals is being recommended to consider repeating this AE inspection within the next 10 years. By repeating this AE inspection Haifa Chemicals will be able to compare the AE data collected during this current monitoring, with the AE data to be recorded during the next inspection. This comparison will determine if there has been any significant changes on the tank's structural integrity between the two inspections;
- Should Haifa Chemicals decides to repeat this AE inspection, we recommend the same number of AE transducers to be installed at the exact same locations as the ones utilized in the present inspection, so a proper comparison can be executed.
- The inspection procedure should attempt to repeat the 6 months operating at a reduced fill level, prior to the fill to 12,000 tons, mirroring the procedure executed in the present inspection.

Limitations of This Report

This report is prepared for the sole benefit of HAIFA CHEMICALS, and the scope is limited to matters expressly covered within the text. In preparing this report, SES has relied on information provided by HAIFA CHEMICALS and, if requested by the HAIFA CHEMICALS, third parties. SES may not have made an independent investigation as to the accuracy or completeness of such information unless specifically requested by HAIFA CHEMICALS or otherwise required. Any inaccuracy, omission, or change in the information or circumstances on which this report is based may affect the recommendations, findings, and conclusions expressed in this report. SES has prepared this report in accordance with the standard of care appropriate for competent professionals in the relevant discipline and the generally applicable industry standards. However, SES is not able to direct or control operation or maintenance of HAIFA CHEMICALS's equipment or processes.

Appendix A: General and per channel AE Data