## STP-PT-021

# NON DESTRUCTIVE TESTING AND EVALUATION METHODS FOR COMPOSITE HYDROGEN TANKS

ASME STANDARDS TECHNOLOGY, LLC

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### TABLE OF CONTENTS

Forewordix			
Ab	stract		X
1	Test Metho	ods	1
	1.1 Summa	arv	1
	1.2 Backgr	ound on the NDE Techniques	1
	1.2 Dackgr 1.2.1	Modal Acoustic Emission	
	1.2.2	Ultrasonic	2
	1.3 Lincolr	n Composites Pressure Vessels	9
	1.4 TransC	Canada/FPC Pressure Vessels	
2	Ultrasonic '	Testing	
3	Modal Aco	oustic Emission Testing – Lincoln Tanks	14
	3.1 Test De	escription	
	3.1.1	Test Concepts	14
	3.1.2	Tank Description	14
	3.1.3	Test Setup	15
	3.2 Pre-dar	mage Proof Testing	
	3.3 Drilled	Hole Testing	
	3.4 Cut Fib	pers Testing	
	3.5 Impact	Testing	
	3.6 Vessel Damage Test Conclusions		
4	Modal Aco	oustic Emission Testing – TransCanada Tanks	
	4.1 Cycle 7	Fests - Vessel G107100007	
	4.1.1	Summary	
	4.1.2	Modal AE Equipment Settings	
	4.1.3	Sensor Layout	
	4.1.4	Flow Noise Waveforms	
	4.1.5	Results and Discussion	
	4.1.6	Graph Legend	
	4.1.7	Cycles 1 to 2631	
	4.1.0	Cycles 2638 to 2662	38
	4.1.10	Cycles 2670 to 5358	
	4.1.11	Cycles 5358 to 7089	
	4.1.12	Last 5000 cycles, up to 12,052	
	4.1.13	Conclusions	
	4.2 Autofre	ettage Tests - Vessels G1074500004, G1074500005, G1074500006 and	
	G1074:	500010	
	4.2.1	Summary	
	4.2.2	Nodal AE Equipment Settings	
	4.2.5	G1074500004 Autofrattage Test	
	4.2.4 1 2 5	G1074500004 Attonic Test	
	4.2.3 496	G1074500004 AL and volumente rest	
	1.2.0	Stor recorde rutoriounge rest	······ +0

	4.2.7	G1074500005 AE Test	47
	4.2.8	G1074500006 Autofrettage Test	47
	4.2.9	G1074500006 AE Test	
	4.2.10	G1074500010 Autofrettage Test	
	4.2.11	G1074500010 AE Test	
	4.2.12	Results and Discussion	
	4.3 Autofrettage and Burst Test – Vessel G107400001		
	4.3.1	Summary	
	4.3.2	Results	50
	4.3.3	Modal AE Equipment Settings	
	4.3.4	Sensor Layout and Coupling Check	
	4.3.5	Autofrettage Test	
	4.3.6	Graph Legend	
	4.3.7	Burst Test	
5	Phased Ser	sor Arrays for Modal AE Measurements	55
	5.1 Introdu	iction	
	5.2 Sensor	Stacking	
	5.2.1	PVDF Sensors	
	5.2.2	Stacked Sensor Study Plate Geometry	
	5.2.3	Location of the Source	
	5.2.4	Stacked Sensor Instrumentation	
	5.2.5	System Settings	
	5.2.6	Sensor Stacking Results and Discussion	
	5.2.7	Aperture Effects	
	5.3 Phased	Arrays for Modal Acoustic Emission	
	5.3.1	Initial Testing	64
	5.3.2	Linear Phased Array Study	64
	5.3.3	Beam Steering Calculations	
	5.3.4	Steel Tank Phased Array Results	
	5.4 Benefits of Stacked Phased Array Sensors for MAE		
	5.5 Conclu	sions	
	5.6 Follow-on Work		76
6	Hydrostatic	c Test Requirements	
7	Finite Elen	nent Analysis (FEA)	
8	Photon Induced Positron Annihilation (PIPA)		
	8.1 Defect	s in Composite Materials	
	8.2 Phase	Contrast Analysis	
	8.3 IPA vs	. PCA	86
Re	ferences		
Ap	pendix A - I	Detailed Study of MAE in the 613-003 (Drop Tested) Data	
Ac	knowledgm	ents	
Ab	breviations	and Acronyms	

#### LIST OF TABLES

Table 1 - TransCanada Tank Testing History	32
Table 2 - G107100007 Cycle Testing	33
Table 3 - FM-1 System Settings	34
Table 4 - Autofrettage Testing	44
Table 5 - FM-1 System Settings	44
Table 6 - FM-1 System Settings	51
Table 7 - Hydrostatic Test Requirements	78

### LIST OF FIGURES

Figure 1 - Computer and Amplifier/Filter Stack for Recording Modal AE Sounds	2
Figure 2 - F-Scan X-Y Scanning Bridge	3
Figure 3 - Close-up of the Scanning Head	4
Figure 4 - Software Screen Showing the Various Displays During a Stiffness Scan	5
Figure 5 - Expanded View of the Dispersion Curve Shown in Figure 4	6
Figure 6 - Laminate Properties (A, B and D Matrices)	6
Figure 7 - Composite Plate Properties Can Be Stored for Later Recall	7
Figure 8 - Time of Flight Plot	8
Figure 9 - Transmit and Receive Channels	9
Figure 10 - Lincoln Composite Pressure Vessel Setup for Pressure Test with MAE 1	0
Figure 11 - Transcanada/FPC 40-ft. Vessel 1	1
Figure 12 - GTM at FPC Shows Effects of .50 Caliber Machine Gun Fire 1	2
Figure 13 - Burst Test of the Fire Damaged GTM 1	3
Figure 14 - Burst Test of a 10-ft. GTM 1	3
Figure 15 - 613-0XX H2 Pressure Vessel 1	4
Figure 16 - 613-0XX Approximate Dimensions 1	5
Figure 17 - 613-0XX Sensor Circumferential Distance 1	6
Figure 18 - 613-0XX Ready for Proof Test 1	6
Figure 19 - 613-001 Sensor Locations 1	7
Figure 20 - 613-001 Before Drilled Holes 1	8
Figure 21 - 613-003 Proof Before Impact 1	8
Figure 22 - 613-018 Proof Before Cut Damage 1	9
Figure 23 - 613-001 Sensor Locations	20
Figure 24 - 613-001 Sensor Locations	20
Figure 25 - 613-001 Drilled Holes	21

Figure 26 - 613-001	21
Figure 27 - 613-001	
Figure 28 - 613-001	
Figure 29 - 613-001	
Figure 30 - 613-001 Proof with Drilled Holes	23
Figure 31 - 613-001 Proof with Drilled Holes	
Figure 32 - 613-018 Fiber Cut Location	
Figure 33 - 613-018 Fiber Cut Size	
Figure 34 - 613-018 Membrane Cut – Low Gain	
Figure 35 - 613-018 Membrane Cut – High Gain	
Figure 36 - 613-018 Dome Cut, High Gain	
Figure 37 - 613-003	
Figure 38 - 613-003	
Figure 39 - 613-003	
Figure 40 - 613-003	
Figure 41 - 613-003	
Figure 42 - 613-003 Proof after Impact	
Figure 43 - 613-003 After Impact and Burst Test	
Figure 44 - G107100007 Sensor Layout	
Figure 45 - Typical Flow Noise Signal	
Figure 46 - Frequency Spectrum of the Flow Noise Signal	
Figure 47 - First Leak Signal	
Figure 48 - Graph Legend	
Figure 49 - Cycles 1 to 2631	
Figure 50 - Cycles 1 to 2631	
Figure 51 - Cycles 1 to 2631	
Figure 52 - Cycles 1 to 2631 Sample Event	
Figure 53 - Cycles 2638 to 2662	
Figure 54 - Cycles 2670 to 5358	
Figure 55 - Cycles 2670 to 5358	40
Figure 56 - Cycles up to 12,052	41
Figure 57 - Cycles up to 12,052	41
Figure 58 - Cycles up to 12,052	42
Figure 59 - End of Cycle Waveform Channel 1	42
Figure 60 - End of Cycle Waveform Channel 2	42

Figure 61 - Sensor Layout for Autofrettage Testing	45
Figure 62 - G1074500004 Autofrettage Test	45
Figure 63 - G1074500004 AE and Volumetric Test	46
Figure 64 - G1074500005 Autofrettage Test	46
Figure 65 - G1074500005 AE Test	47
Figure 66 - G1074500006 Autofrettage Test	47
Figure 67 - G1074500006 AE Test	48
Figure 68 - G1074500010 Autofrettage Test	48
Figure 69 - G1074500010 AE Test	49
Figure 70 – Sensor Layout for Burst Test	51
Figure 71 - Autofrettage Test	52
Figure 72 - Graph Legend	52
Figure 73 - Burst Test	53
Figure 74 - Burst Test	53
Figure 75 - Plate Geometry	57
Figure 76 - FM1 Modal Acoustic Emission (MAE) Data Acquisition and Analysis System	58
Figure 77 - Stacked PVDF Sensors on the ABS Plate	59
Figure 78 - Stacked PVDF Sensors Compared to B1025 and B225-5 Sensors	60
Figure 79 - Stacked PVDF Sensors Compared to the B1025 Sensor	60
Figure 80 - Serial Wiring of the PVDF Transducers to Increase the Voltage Output	61
Figure 81 - PVDF Stacked Sensor Analog Output	61
Figure 82 - PVDV Responses from Figure 81 and Comparison with the B1025 Output	62
Figure 83 - PVDF Analog Summation Versus the Digital Summation of the Sensor Stack	62
Figure 84 - A Schematic of Phased Array Detection and Source Location	64
Figure 85 - Array Geometry and Coordinate System	65
Figure 86 - 0 Degree Lead Break Results – Directional Rays	66
Figure 87 - 0 Degree Lead Break Results – Non Time-Shifted	67
Figure 88 - 0 Degree Lead Break Results – Time-Shifted	67
Figure 89 - 45 Degree Lead Break Results – Directional Rays	68
Figure 90 - 45 Degree Lead Break Results – Non Time-Shifted	68
Figure 91 - 45 Degree Lead Break Results – Time Shifted	69
Figure 92 - 90 Degree Lead Break Results – Directional Rays	69
Figure 93 - 90 Degree Lead Break Results – Non Time-Shifted	70
Figure 94 - 90 Degree Lead Break Results – Time-Shifted	70
Figure 95 - Tank and Array Used for the Phased Array Tests	71

Figure 96 - (12, 12) Lead Break Position, Directional Rays	72
Figure 97 - (12, 12) Lead Break Position, Time Shifted Waveforms	72
Figure 98 - (6, 12) Lead Break Position, Directional Rays	73
Figure 99 - (6, 12) Lead Break Position, Time Shifted Waveforms	73
Figure 100 - (12, 24) Lead Break Position, Directional Rays	74
Figure 101 - (12, 24) Lead Break Position, Time Shifted Waveforms	74
Figure 102 – Application of Phased Arrays	75
Figure 103 - Path 1 in Long Seam Weld for Fatigue Data. Path Starts at the Vessel ID	81
Figure 104 - Path 2 in Long Seam Weld for Fatigue Data. Path Starts at the Vessel OD	82
Figure 105 - Path 3 in Long Seam Weld for Fatigue Data. Path Starts at the Vessel ID	82
Figure 106 - Stress Path Across Offset Shell to Head Weld	83
Figure 107 - 613-003 12.5 ksi Proof Test after 6-ft. Drop	88
Figure 108 - 613-003 P to 12.5 ksi after 6-ft. Drop	89
Figure 109 - 613-003 P to 12.5 ksi after 6-ft. Drop	89
Figure 110 - 613-003 P to 12.5 ksi after 6-ft. Drop	90
Figure 111 - 613-003 P To 12.5 ksi after 6-ft. Drop	90
Figure 112 - 613-003 P To 12.5 ksi after 6-ft. Drop	91
Figure 113 - 613-003 P= 12.5 ksi after 6-ft. drop	92
Figure 114 - 613-003 P= 12.5 ksi after 6-ft. drop	92
Figure 115 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	93
Figure 116 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	94
Figure 117 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	95
Figure 118 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	95
Figure 119 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	96
Figure 120 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	97
Figure 121 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	98
Figure 122 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	99
Figure 123 - 613-003 High Gain Test to P= 12.5 ksi after 6-ft. drop	100

#### FOREWORD

The report is the result of a collaborative research project sponsored by the National Center for Manufacturing Sciences, Inc. (NCMS) and performed under Collaborative Agreement Number 200589-130163. Project participants included ASME Standards Technology LLC, Digital Wave Corporation, Lincoln Composites and TransCanada CNG Tech. LTD. The project participants provided matching contributions of labor and expenses to the project.

It is anticipated that automotive fuel tanks with a capacity of 10,000 psi compressed hydrogen will be required in order to commercialize fuel cell vehicles (FCVs). The infrastructure supporting refueling of these vehicles will require storage, transportation and portable pressure vessels with operating pressures up to 15,000 psi compressed hydrogen. Due to cost and weight constraints, the use of composite pressure vessels will be a critical new technology to enable the development of the FCV fuel tanks and the supporting hydrogen infrastructure. New code rules will be required to enable commercialization of the technology and achievement of the DOE hydrogen program goals.

Destructive burst pressure tests are conducted by composite pressure vessel manufacturers to verify the integrity of their products and to meet existing rules. These destructive tests are costly, require significant time to perform and must be performed under strict safety guidelines by trained personnel. Destructive testing increases overall manufacturing cost in the form of parts, labor, equipment– hydraulic volume tanks, safety equipment (burst chambers), employee training, insurance premiums, designated facilities, etc. Additionally, destructive testing also increases lead times, further making manufacturers less competitive. These tests are often conducted more than once as test results from a single pressure burst test are not considered sufficient for a single design or lot. Although this may still be cost effective for manufacture of orders for multiple duplicate composite pressure vessels, this may be cost prohibitive for single or custom pressure vessel orders. Non-destructive testing evaluation methods can substantially reduce manufacturing cost by eliminating extensive and costly testing periods.

The non-destructive evaluation methods, Acoustic Emission (AE) and Modal AE, proposed for hydrogen applications are transferable to other industries (petrochemical, aerospace, military, medical and energy–LPG and natural gas) and have been used in leak detection applications for years with media such as petroleum, helium, water, air, oxygen, nitrogen and other gases.

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#### ABSTRACT

This report includes a study of various nondestructive evaluation (NDE) techniques for composite overwrapped pressure vessels intended for gaseous hydrogen infrastructure applications. The majority of the study focuses on Model Acoustic Emissions (MAE) techniques. Testing was performed on various composite tank designs including small high pressure plastic-lined fully-wrapped composite pressure vessels designed for portable, stationary or vehicular storage and large steel-lined hoop-wrapped pressure vessels designed for bulk transport and stationary storage. MAE testing was performed by Digital Wave Corp. on vessels provided by Lincoln Composites and TransCanada.

MAE testing of Lincoln Composites plastic-lined fully-wrapped 10,000 psi composite pressure vessels was performed at the Lincoln facilities in April 2007. Tank damage was simulated through drilled holes, membrane cuts and a drop test, and subsequent proof and burst testing was performed while monitoring with MAE techniques. The manufacturing consistency was confirmed by MAE. Generally, it was observed that the vessels failed at damage sites. Drilled holes all the way through the composite resulted in lowest burst pressure, followed by impact from 6-ft. drop onto concrete, and finally the cut fibers. MAE picked up the newly introduced damage very well on first pressurization after damage occurred. Emission did not completely stabilize, indicating that the damage did continue to grow during the pressure holds. At the higher sensitivity setting, MAE Frictional Emission (FRAE) was picked up on every cycle after damage. Location of damage was very clear acoustically using MAE techniques.

MAE testing of six TransCanada large steel-lined hoop-wrapped composite pressure vessels was performed in October 2007. The test program included cyclic testing, pressure/autofrettage and burst testing while monitoring using MAE techniques. During cycle testing crack growth was detected in the metallic head to shell welds at both ends of the vessel. The number of cycles sustained before fatigue failure due to this cracking exceeded the required 10,000 cycles. This was determined from the acoustical signal produced by a leak source. During the pressure (autofrettage) tests, the cumulative events versus time curves showed a characteristic "roll over" during pressure load holds in the AE test in all cases. There were few or no events during the load holds and very few events during the AE test. This is consistent with fracture mechanics reasoning since the AE test pressure is so much lower than the autofrettage pressure. It was observed that autofrettage cycles at 1.5 x operating pressure instrumented for AE detection would bound an AE cycle at 1.1 x operating pressure. This conclusion is in agreement with previous experience on various other pressure vessels.

A study and laboratory testing of MAE sensor arrays constructed of piezoelectric material, polyvinylidene film (PVDF), was performed by Digital Wave Corp. in February 2008. This study looked at two ways to enhance the sensitivity of the PVDF film transducers, 1) sensor stacking and analog summation of the sensor outputs, and 2) digital summation of the sensor outputs. It was observed that stacked sensors increased sensitivity of detection, there was no phase distortion due to stacking and reducing sensor size can reduce aperture affects and increase bandwidth. A phased array configuration for modal acoustic emission (MAE) can determine direction of source and possibly distance. Phasing of signals for source location is possible and aids in mode identification and source location, which is very sensitive to variations in arrival time differences. Sensor placement is also extremely important, and the sensitivity to array geometry must be studied.

This report also includes additional discussion of other relevant NDE and analysis techniques including a study of composite tank hydrostatic test requirements, a finite element analysis (FEA) and fracture mechanics analysis on composite reinforced pressure vessels predicting failures observed during testing and indicated using AE techniques, and a discussion of photon induced positron annihilation (PIPA) which is a potential NDE process that can assess material damage at the near-molecular level.