A7621-18:CRC-CD8.1

Examination Of The Nondestructive Evaluation Of Composite Gas Cylinders

FINAL REPORT

September 2002

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Acknowledgments

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1.0 EXECUTIVE SUMMARY

Several NDE methods were evaluated according to available literature, based on their potential ability to inspect composite gas cylinders, by conducting a review of the current practice and state of the art in inspecting composite gas cylinders. Based on this literature review (summarized in Table 1-1), NTIAC arranged to have several vendors and service providers conduct a preliminary feasibility study of inspecting a small sampling of cylinders.

Table 1-1. Summary of the findings of the literature review conducted for the composite gas cylinders feasibility study. The results of the literature review were used to select several system vendors to participate in the feasibility study.

NDE Technique	Applicability to Composite Cylinder Inspection
Ultrasonics	Inspector learning curve an issue but should be applicable
Eddy Current	Applicable for high carbon-content composites but complex electrical conductivity hampers widespread adoption, some question about detecting subtle damage
Magnetic Particle	Not applicable (only for ferromagnetic materials)
Liquid Penetrant	Potential fouling concern, not able to detect subtle damage (e.g. creep)
Acoustic Emission	Widely used in inspecting composites, R&D investment potentially an issue
Micro/Millimeter Wave	Technically possible but has a very low penetration/high attenuation (> 4dB/mm) and difficult to introduce into material
X-Ray Radiography	Technically feasible but difficult to distinguish between multiple layers of low-density materials, would require numerous tangential "shots" of the cylinder
Visual	Currently in use, unable to detect subtle damage (e.g. "creep"); consistently undersizes actual extent of damage
Shearography	Shown to work for impact damage, may be less applicable for subtle damage (e.g. heat damage)
Thermography	Applicable with a complete understanding of the complex nature of composite; initial equipment cost relatively high
Thermoelastic Stress Analysis	Applicable with good correlation with physical state but found to be highly dependent on surface conditions (temperature, stress) and requires extra calculation techniques to correlate with complex interior damage (e.g. delaminations)

The system vendors invited to participate in the feasibility study are detailed in Table 1-2, along with a summary of their results. Thermoelastic Stress Analysis (TSA, also known by the trade name SPATE) was identified in the literature review as a potentially viable inspection technique, but due to the relative obscurity of the technique no system vendor/service provider willing to participate in the feasibility study were found.

Table 1-2. Summary of the feasibility study participants: inspection technique and summary of findings.

Inspection Particulars	**Study Participants**			
	Lockheed Martin	Physical Acoustics	Thermal Wave Imaging	Don Bray Engineering
Inspection Technique	Ultrasonics (Laser)	Acoustic Emission	Thermography	Ultrasonics (Critically Refracted Longitudinal Waves: L_{CR})
Inspection Premise	LaserUT™ system uses lasers to induce ultrasonic wave propagation in cylinders; properties of wave dependent on damage condition of cylinder	Damaged cylinders emit acoustic noise when brought to pressure; network of piezoelectric sensors detect the noise	Thermal properties of cylinder change with damage condition; infrared camera detects hot/cold spots	L_{CR} waves are sensitive to stress conditions in the cylinder, which are in turn sensitive to damage condition
Summary of Findings	Unable to generate ultrasonic waves in translucent composites	Able to accept or reject cylinders based on AE activity	Couldn't achieve 100% penetration of composite but able to detect near-surface anomalies	Able to demonstrate ultrasonic wave propagation through composite

Based on these initial feasibility studies, NTIAC believes that acoustic emission and thermography hold the most promise in terms of viable composite cylinder inspections, with ultrasonics showing some degree of promise but limited by the realities of composite cylinder construction.

2.0 INTRODUCTION

Figure 2-1. Compressed gas cylinders: fiberglass (upper left), Kevlar (center), and carbon-wrapped (lower right). Fiberglass and carbon cylinders were used for the initial feasibility study; Kevlar cylinders, although not used during this phase of study, were acquired for follow-on work.

Currently the requalification and recertification process for composite wrapped gas cylinders (Figure 2-1) requires hydrostatic testing followed up with a visual examination, repeated every three years up to a maximum of 15 years.

This procedure introduces two primary issues-the first, the requalification process tends to be highly operator-dependent, based on the visual acuity and experience of the inspector. At the same time, a visual inspection can miss critical damage that can adversely affect the structural integrity of the cylinder. Recent studies have found that visual inspection is capable only of detecting damage that exceeds 20% of full strength [1].

A reliable method or methods of nondestructive evaluation (NDE) that can reduce the chances of in-service failure and at the same time maximize the lifetime of the cylinder, beyond the current 15 year lifetime, is desired.

Goal: Reliable and quantifiable NDE method for inspection and recertification of composite high pressure gas cylinders.

With this goal in mind, the United States Department of Transportation's Research and Special Programs Administration contracted NTIAC, the Nondestructive Information Analysis Center, to find an NDE procedure to meet this challenge. As part of the project, NTIAC conducted an extensive literature search and a state-of-the-art survey on NDE of composite cylinders, the results of which are presented in this report. Building on NTIAC's experience in researching the nondestructive evaluation of 6351-T6 alloy aluminum gas cylinders, the NDE method(s) would have to meet several important criteria before any use to assess operational damage and to use as a basis for requalification:

- Equipment must be affordable
- Method(s) must have low level of dependence on operator skill and subjectivity (must be easy to learn and use)
- Method(s) must be relatively quick

References:

1. Beeson, Harold D., Davis, Dennis D., Ross, William L. Sr., and Tapphorn, Ralph M. **"Composite Overwrapped Pressure Vessels."** NASA White Sands Test Facility: Report Number NASA/TP-2002-210769, 2002.

3.0 PROCEDURE

3.1 Literature Review

NTIAC used a three-prong approach to the initial Information Gathering Task:

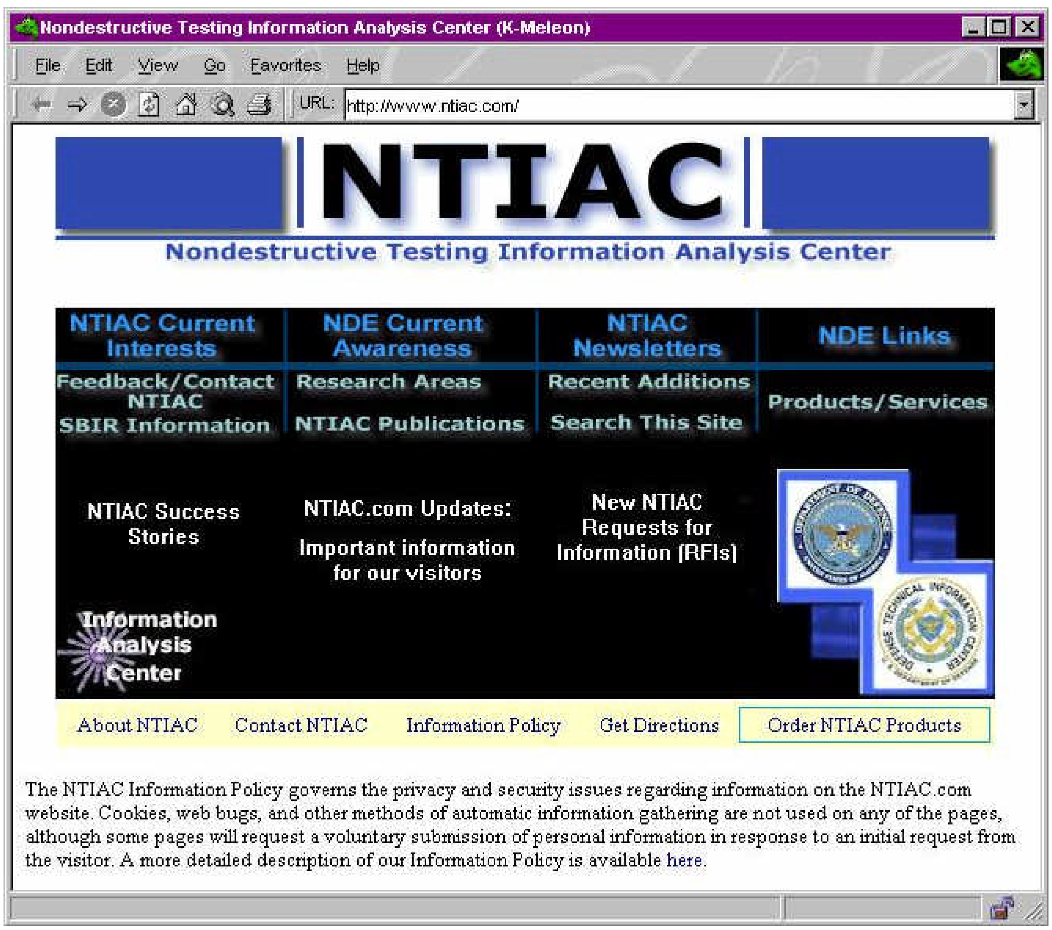

Figure 3-1. Composite cylinder RFI announcement on the NTIAC web site.

1. Literature Searches
    - NERAC
    - NTIAC Library/Databases
    - DROLS
    - University of Texas
    - Internet Search Engines
    - Industry/Trade Groups
        - Gas Research Institute (natural gas vehicle research)
        - Compressed Gas Association
    - Patent Searches
        - US Patents (1971 - present)
        - European Patents (1980 - present)
        - Japanese (1976 - present)
2. Requests For Information (RFIs) releases
    - NTIAC Web Site (http://www.ntiac.com)
    - December 2001 NTIAC Newsletter
    - NTIAC News email mailing list (http://lists.ntiac.com/mailman/listinfo/ntiacnews)
    - NDT Email listserv
    - Newsgroups (the "sci.*" groups)
        - engr.chem
        - materials
        - polymers
        - techniques.testing.nondestructive
3. Interviews

3.2 Literature Review Conclusions

In their final report to Space and Missile Systems Center [1], the Aerospace Corporation investigators presented a summary graphic of their conclusions (somewhat subjective in that it was not based on hard evidence) on the applicability of several common NDE techniques to detecting impact damage in COPVs, reproduced in Figure 3-2.

In a recent NTIAC Technology Assessment [2], NTIAC summarized the methods available for two important types of damage of interest in fiber reinforced polymer composites inspection:

- Porosity (distributed voids): a common problem in the manufacturing process, particularly for laminated structures (e.g. CFRP composites). Ultrasonic

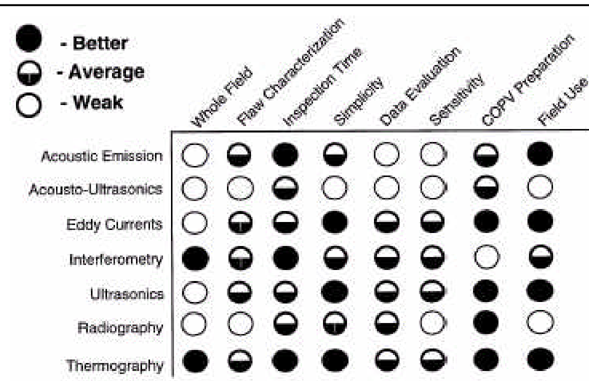

Figure 3-2. Summary graphic of the Aerospace Corporation's evaluation of basic NDE techniques for detection of impact damage in COPVs.

techniques (narrow- or broad-band approach) most applicable detection methods.

- Delaminations: visual inspection, tap testing, resonance methods, ultrasonics, thermography, eddy current testing, X-Ray radiography have all been used with varying degrees of success. Shearography shows tremendous potential and is gaining more acceptance, despite the high equipment cost.

The Technical Assessment makes the additional point that while thermography (and by extension, TSA) show a lot of promise, not enough is known about the thermal properties of many composites and further research is required to optimize these techniques.

Of the 11 techniques evaluated in the process of conducting the literature review, four seemed to hold the most promise. These four were chosen as the ones that not only showed the most promise, but also were also the most widely applicable in terms of the variety and extent of damage that were detectable, as well as being generically applicable to composite structures in general. Other potentially useful NDE technologies, such as eddy current testing or microwave testing, are potentially applicable for one particular type or subtype of composite, but are fundamentally unable to inspect other types.

The techniques identified in the literature review that appear to hold the most promise for inspecting composite overwrapped compressed gas cylinders were:

Ultrasonics
Acoustic Emission
Thermography
Thermoelastic Stress Analysis (TSA)

Two of the techniques, ultrasonics and acoustic emission, did not receive as strong a recommendation in the Aerospace Corporation report. However, given our extensive experience in applying both techniques to composites evaluations, coupled with our experience in cylinder inspections, we remained confident that both were applicable. In addition, it is worth noting that the Aerospace report was strictly interested in impact damage, whereas the NTIAC work is interested in every other type of damage.

Thermography received a strong recommendation in the Aerospace report for detecting impact damage. The literature review suggests that while thermography is indeed applicable for detecting other types of damage, the quantitative analysis of these damage types with infrared thermography may not be as straightforward as for impact damage, given the complex thermal behavior of a composite and its multi-layer structure. Nevertheless NTIAC believed the technique viable based on both the literature review and previous experience.

The fourth technique, TSA or SPATE, was not addressed in the NASA/Aerospace work being a relatively obscure technology (in comparison to NDE mainstays such as ultrasonics and eddy current inspections). Although shown to have complications due to the complex thermal behavior of composites (as is the case for thermography), experimental evidence suggests the technique is still potentially viable as a rapid method of characterizing the composite cylinders.

All of the techniques investigated in the literature review that show even a glimmer of promise share a common theme: further research and development is required. In many instances this is due to the relatively recent arrival of the composite, in particular of the many different "recipes" in the field. In large part other than specific mechanical properties, little has yet been learned about thermal, electromagnetic, and acoustic properties. As these composites become more mainstream, however, and their adoption increases while the industry matures, these unknowns will be addressed, thereby improving the state of the art in their nondestructive evaluation.

References:

1. Chang, J.B. **"Enhanced Technology for Composite Overwrapped Pressure Vessels."** Aerospace Corporation: Report Number TR-99(8504)-1, Technical Summary of Final Report to Space and Missile Systems Center, Air Force Materiel Command, 2001. Johnson, E.C., and Nokes, J.P. **"Nondestructive Evaluation (NDE) Techniques Assessment for Graphite/Epoxy (Gr/Ep) Composite Overwrapped Pressure Vessels."** Aerospace Corporation: Report Number TR-98(8504)-3, Prepared for Space and Missile Systems Center, Air Force Materiel Command, 1998.

2. Osborne, M.C., and Moran, A.L. **"Stress Pattern Analysis by Thermal Emission of Plain Weave Carbon Fiber/Epoxy Resin Composite Iosipescu Specimens with Three Different Notch Angles."** ASTM Journal of Testing and Evaluation: Volume 29, Issue 5, 2001, pp. 453-459.

3. Coughlin, C.R. **"Inspection Of Composite "Hoop Wrapped" Gas Cylinders Literature Review."** Submitted April 2002 as part of the current effort.

3.3 <u>Feasibility Studies</u>

The initial literature review conducted by NTIAC identified several candidate technologies as potentially viable for inspecting the composite gas cylinders. Based on these findings, NTIAC invited several system vendors and service providers to participate in an initial feasibility study.

For the purposes of the feasibility study, a complete inspection of a known set of cylinders was not required. Rather, the feasibility study was designed to return a "go/no-go" answer on whether the inspection method could potentially be used to inspect the cylinders, as a roadmap for follow-on studies. To this end, NTIAC provided each of the study participants six composite cylinders for a preliminary investigation (Table 3-1). Cylinders 1, 2, and 3 are new carbon overwrapped cylinders with service pressure of 4500 psi. Cylinders 1 and 3 show visual indication of impact damage (Figure 3-3). Cylinders 4, 5, and 6 are fiberglass wrapped cylinders with service pressure of 2216 psi.

Table 3-1. Specifications of the sample cylinder set sent to all the feasibility study participants.

Cylinder	TC-SU	DOT-E	S/N	Luxfer Part Number	Service pressure PSI	Condition
1	5134-310	10915-4500	IL35248	L65G	4500	Damaged
2	5134-310	10915-4500	IL35250	L65G	4500	New
3	5134-310	10915-4500	IL35249	L65G	4500	Damaged
4	--	7235-2216	WK196368	--	2216	Retired (Made 5-88, Certified 12-95)
5	--	7235-2216	WK30055	--	2216	Retired (Manufacture Date Unknown, Certified 2-94)
6	--	7235-2216	WK583762	--	2216	New

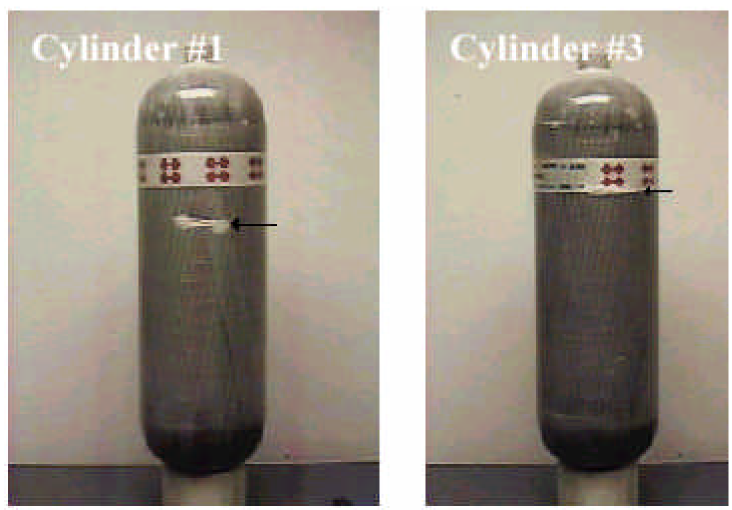

Figure 3-3. Illustration of impact damage on Cylinders 1 and 3.

The study participants took a day to have a very quick look at the six cylinders, wrote a brief summary of their findings, and reported whether they felt their system and method would be viable for full inspections. An introduction to the systems used follows.

3.2.1 Laser Ultrasonics: Lockheed Martin

Laser ultrasonic testing operates with two lasers: one to generate ultrasound in the part by a mechanism called thermoelastic expansion and the other to detect the ultrasonic vibrations as they return to the top surface (Figure 3-4). In the thermoelastic generation process, the energy absorbed from the laser is converted into heat in the top 10 to 100 microns of the surface. The resulting temperature rise creates a local expansion of the material that does not damage or visibly alter the part. If the heating laser pulse duration is short (10 to 100 nanoseconds) then the expansion will be in the frequency of ultrasound (1 to 10 MHz). The efficiency of this mechanism depends on the laser wavelength and associated optical penetration depth.

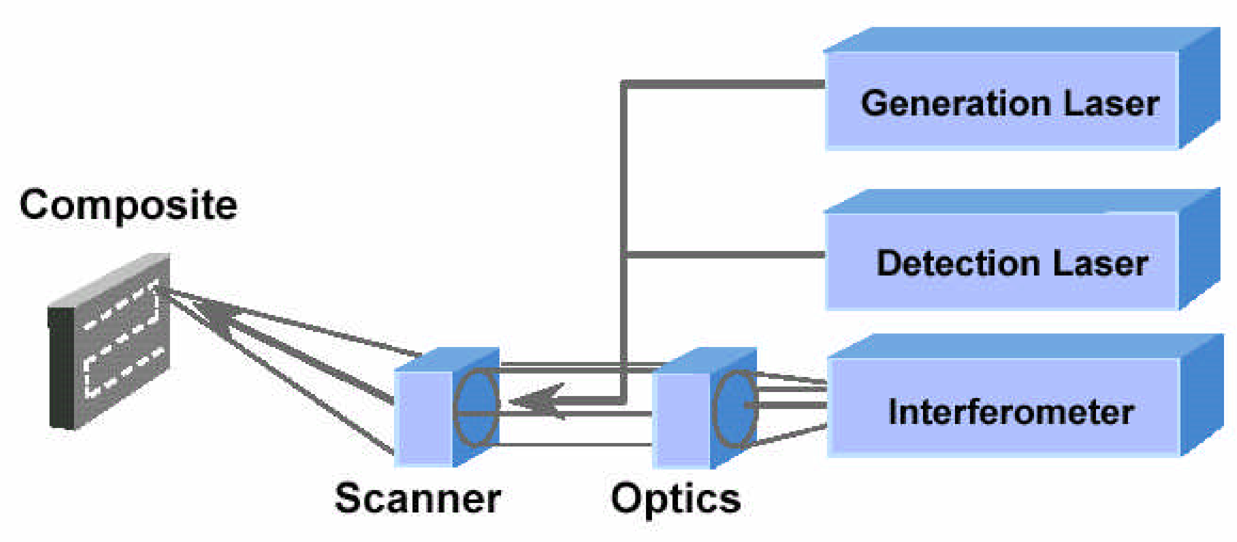

Figure 3-4. Schematic of a laser ultrasonic system.

Thermoelastic generation typically works well on materials with a thin resin layer on the surface. Painted surfaces can also work well. The main advantage of this generation method is that the ultrasound will propagate perpendicular to the surface, independent of the angle of incidence of the laser beam. This allows generation of ultrasound in complex shaped parts at angles as high as ±45° off axis, compared to conventional water-coupled transducers that must remain within a few degrees of the surface normal.

The detection laser is coaxial with the generation laser and illuminates the same point where the ultrasound is produced. Unlike the generation laser, which ideally is absorbed by the composite, this laser scatters off the composite surface. The collected scattered light is analyzed by an interferometer to extract the ultrasonic signals that are "imprinted" on the laser as phase and frequency modulations caused by the moving surface. The ultrasonic signals extracted are fundamentally the same as those obtained with conventional systems and can be analyzed using similar methods.

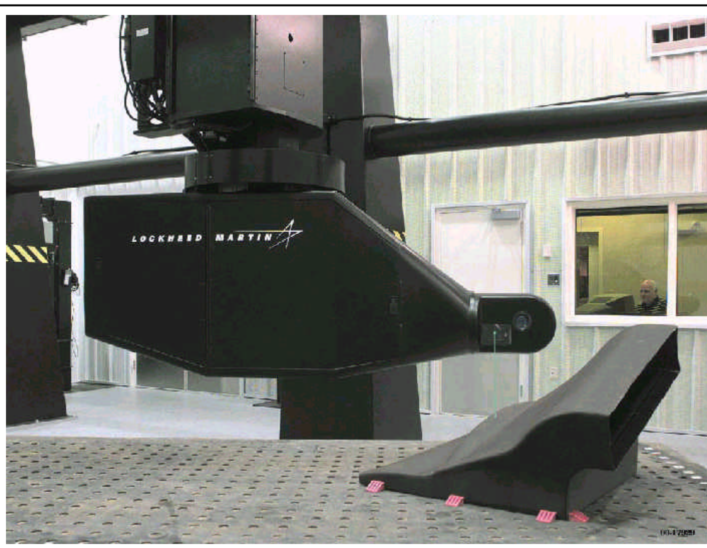

Figure 3-5. Photograph of the Lockheed Martin LaserUT™ system testing a complex composite duct.

Finally, the two laser beams are indexed over the composite surface with an optical scanner to produce traditional NDE images. This all-laser approach greatly simplifies the scanning requirements because the shape of the part is no longer critical for a successful ultrasonic test.

Lockheed Martin has built two LaserUT systems (Figure 3-5), referred to as the Alpha and Beta facilities. These two systems are similar in design, but the inspection envelope of the Alpha gantry robot (52ft × 27ft × 21ft) is much larger than Beta. Both systems use a short-pulsed CO_2 laser to generate the ultrasound and a long-pulsed diode-pumped Nd:YAG laser with a dual differential confocal Fabry-Perot interferometer for ultrasound detection.

These lasers are not eye-safe and the inspection cell is interlocked to protect the operators. The two lasers are optically combined to produce a coaxial beam that is about 5mm in diameter at the composite surface. Inspection depth-of-field is fairly large and allows the part standoff distance to vary between 5 to 8 feet from the optical scanner. Beam indexing (optical scanning) is done using a high-speed two-mirror galvanometer scanner with a 50mm clear aperture.

A five-axis gantry robot moves the inspection head to the best position for scanning each region of a part. Scan coverage can be as large as 6 by 6 feet for a single inspection view. Parts with significant contour are typically sectioned into a series of smaller regions so each subsection remains within the constraints of the system. Scanning constraints are based on the generation efficiency and optical scattering properties of the material, but typical values are $\pm 45^{o}$ angle of incidence and a typical working distance of 6 feet from the surface.

All ultrasonic waveforms are digitally captured, processed and permanently stored while the inspection point is indexed over the composite surface. Real-time data analysis tools are available to the operator that greatly speed the inspection/analysis process. Data management is performed with an automated archival system and an Oracle database. The current LaserUT system operates at a maximum inspection rate of 400 points per second and is limited by the pulse rates of the lasers. The inspection coverage rate is related to the index step size required for the material under test, which is usually based on the size of defect that must be found. A 400Hz scan rate with .080 inch steps equates to an area coverage of about $64ft^2$ /h.

3.2.2 Acoustic Emission: Physical Acoustics Corporation

Each of the cylinders were instrumented with two PAC R15I sensors (150 kHz resonant frequency), and hydraulically pressurized to the predetermined test pressure while monitoring with acoustic emission (AE). Two sensors were placed 8 inches apart from each other in a straight line on the longitudinal direction of the cylinder. The mid-point of the two sensors was approximately at the mid-hoop of the cylindrical portion of each cylinder. For two damaged cylinders, the sensor locations relative to the damage site are shown in Figure 3-6. An illustration of an AE system inspecting composite gas cylinders is shown in Figure 3-7.

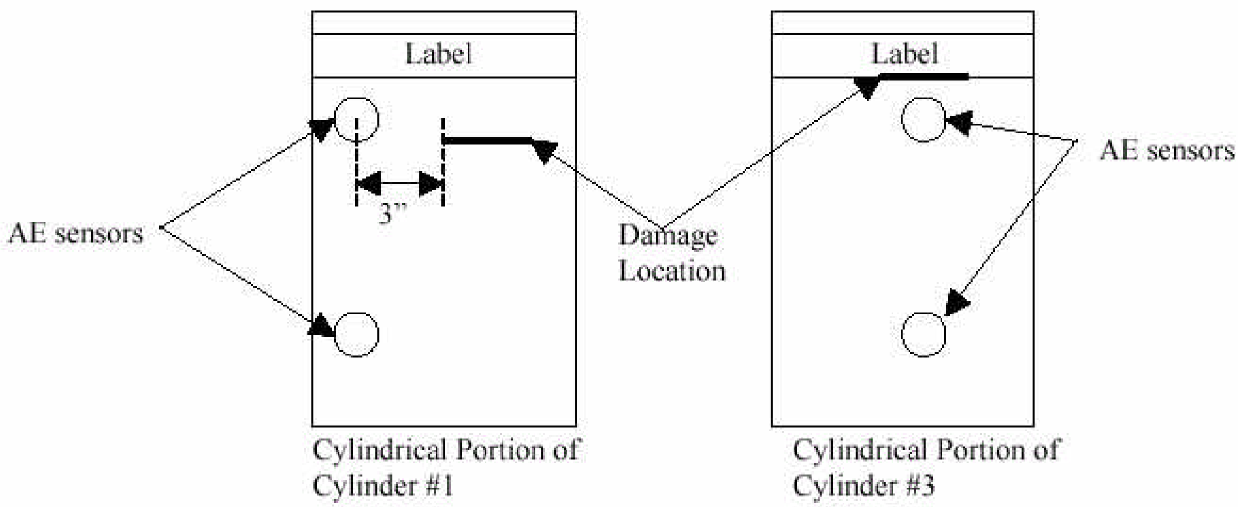

Figure 3-6. Illustration of sensor location on two of the damaged cylinders.

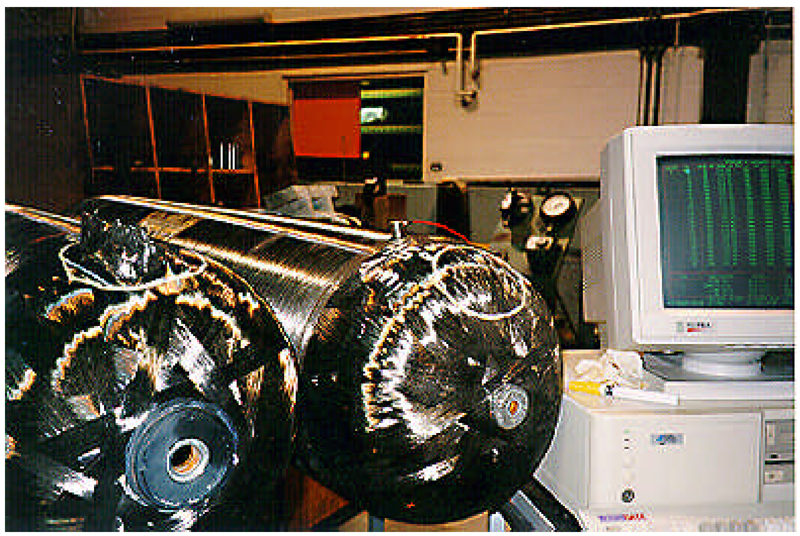

Figure 3-7. Assessment of composite compressed natural gas cylinders following drop tests, from work conducted in 1999 for Transport Canada by Powertech Laboratories. The cylinder on the right is undergoing acoustic emissions testing to assess damage. The one on the left has been pressurized to failure.

Cylinders 1, 2, and 3 were tested individually. Each of them was pressurized to 4950 psi or 110% of the service pressure and held for 10 minutes at this pressure. Cylinder 4, 5 and 6 were tested simultaneously during the same pressure cycle. They were hydraulically pressurized to 2450 psi (110% of the service pressure), and held at this pressure for 10 minutes. At this point, very little emission was observed on all three cylinders. The pressure was then raised from 2450 psi to 2770 psi (125% of the service pressure), and a 10-minute hold was performed at 2770 psi.

3.2.3 Infrared Thermography: Thermal Wave Imaging, Inc.

Thermal Wave Imaging conducted the inspection using standard pulsed thermography equipment, a schematic representation of which is illustrated in Figure 3-8. In pulsed thermography, light is used to heat the surface of the sample, and an infrared camera is used to detect changes in the surface temperature as the sample cools. A dedicated computer system analyzes the cooling behavior of each point on the sample and creates an image of the subsurface structure. Although other energy sources or detection methods may be used to address a particular problem, the underlying principle remains the same.

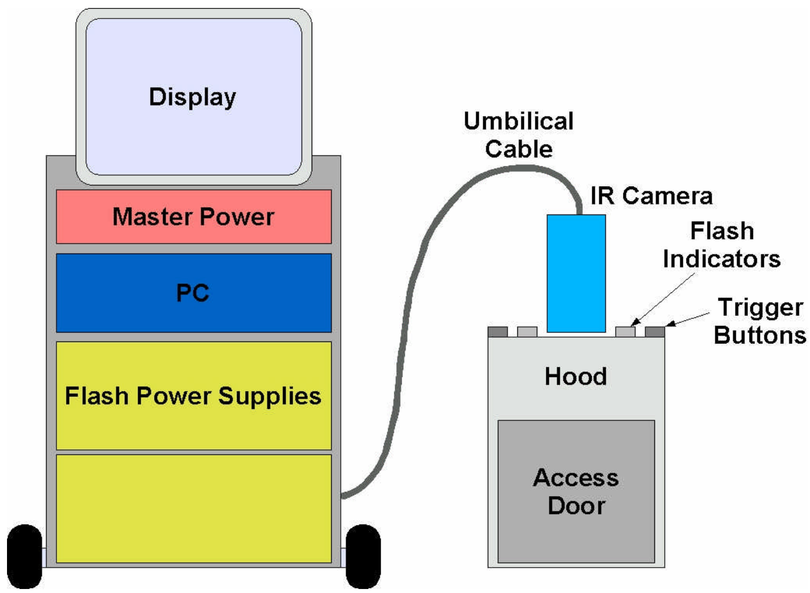

Figure 3-8. Schematic of the thermography system used to inspect the composite gas cylinders.

Figure 3-9. The EchoTherm NDT system used to inspect the composite cylinders.

The inspection was performed using the EchoTherm32 NDT system (Figure 3-9) and a InSb FPA IR camera operating at 60 Hz in the 3-5 mm spectral range. A thin layer of black washable paint was applied to the outer surface to increase optical absorption and IR emmissivity of the sample surface.

3.2.4 L_{CR} Ultrasonics: Don E. Bray Engineering, Inc.

The L_{CR} technique uses critically refracted longitudinal (L_{CR}) waves to map stress fields. As a result of the mapping process, an engineer can determine if unexpected stresses are present, and if corrective action is needed. The L_{CR} ultrasonic technique indicates stress through the acoustoelastic principle where small variations in strain affect the wave speed. By measuring the wave speed (or travel-time between known points) the change in stress can be calculated. Other material variations such as texture and temperature also affect the travel-time.

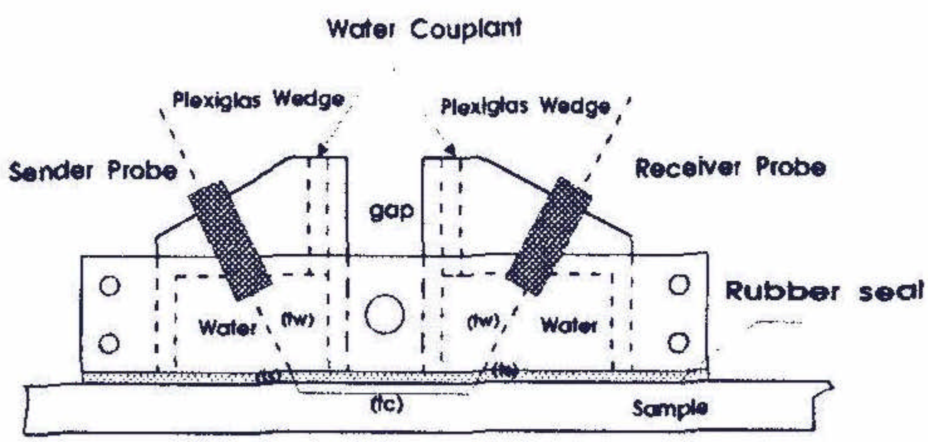

Figure 3-10. Schematic of an L_{CR} transducer shoe.

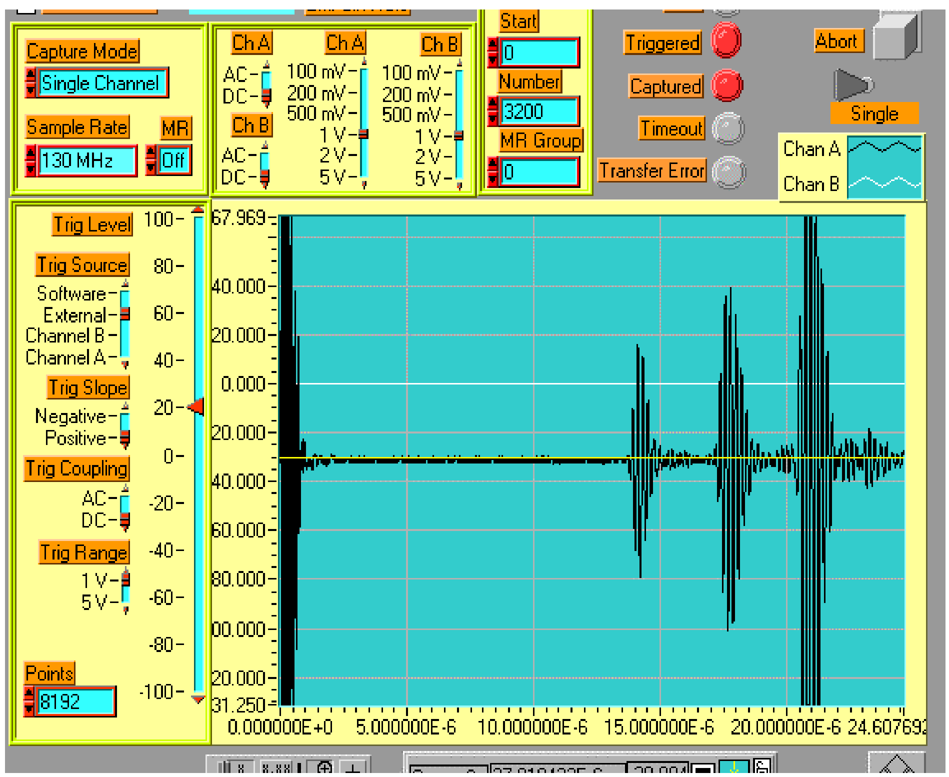

Figure 3-11. L_{CR} waveform captured on a PC.

The acoustic velocity in the composites is measured using standard ultrasonic transducers, in order to calculate the angle of incidence to be used for L_{CR} inspection and to design the probe shoe. An example of a transducer shoe for L_{CR} inspections is shown in Figure 3-10.

The L_{CR} system itself is essentially the same as a standard ultrasonics inspection system: an ultrasonic pulser transmits an ultrasonic wave through the transmitting probe and receives it through one or more receiving probes. The resulting waveform is read into a data acquisition system and analyzed. Figure 3-11 shows an L_{CR} waveform captured on a PC.

4.0 RESULTS

4.1 Laser Ultrasonics

Lockheed Martin's LaserUT system encountered some difficulties with the composite cylinders. Specifically, the composite wraps tend to be optically transmittive in the infrared part of the spectrum, which made it difficult to generate ultrasonic waves with the infrared CO_2 excitation laser. The incident laser light tends to transmit through the composite to the aluminum shell rather than absorbing in the near-surface region of the composite, as required for thermoelastic generation of ultrasonic waves. This is illustrated graphically in Figure 4-1.

To address this problem, Lockheed Martin attempted to make the composite less translucent to the excitation laser. The LaserUT team used Scotch-Brite scouring pads to roughen the cylinder's surface, and painted a smallish section of the cylinder in an attempt to decrease transmittivity. However, even with these measures the LaserUT system was not able to conduct a meaningful scan of the cylinders.

Michael Thomas, Lockheed Martin's LaserUT Manager, indicated in follow-up correspondence that it may be possible to successfully inspect the

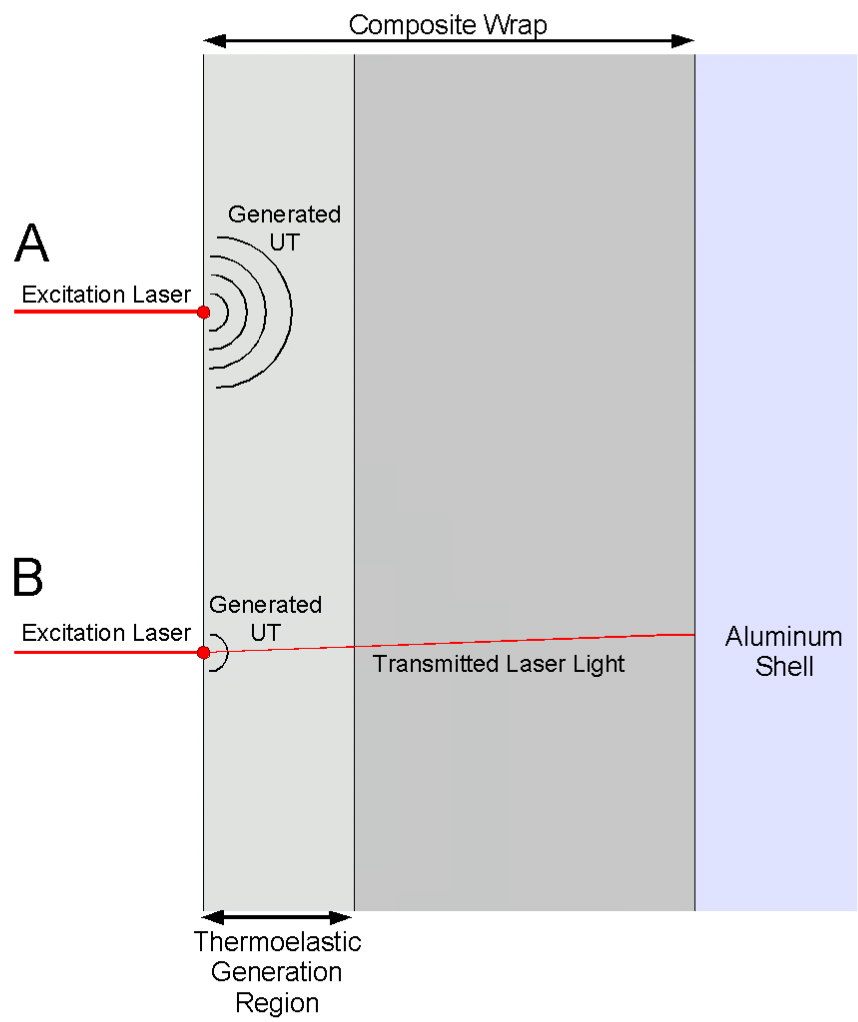

Figure 4-1. Illustration of the difficulties encountered during the laser ultrasonics feasibility study. The desired scenario (A in the figure) is to have the laser light convert to ultrasonic waves within 10-100 mm of the surface of the composite. What actually happens (B in the figure) is that only part of the laser light converts, while part is transmitted through the composite.

cylinders given additional time. The LaserUT system is similar to a CNC system in that the inspections are programmed into the system. Due to the time constraints of this feasibility study, Lockheed Martin restricted their efforts to minor modifications to existing programming and inspection algorithms. Given additional time, a custom inspection program can be written for the composite gas cylinders to provide for a complete inspection.

4.2 Acoustic Emission

The AE results in terms of AE counts are summarized in Table 4-1 and Table 4-2. For all cylinders, the listed AE counts include those acquired during both the pressure rising period and the pressure holding period. For the pressure rising period, the AE counts acquired below 1000 psi were not included. Figure 4-2 shows the AE counts versus pressure for all cylinders.

Table 4-1. AE test results in terms of AE Counts [1] for Cylinders 1-3.

Cylinder	Condition	AE counts [2]	AE counts [3]	AE counts [4]
1	Damaged	**190000**	110500	79500
2	New	**18400**	9500	8900
3	Damaged	**430000**	393000	37000

Notes: [1] AE counts shown in this table were acquired from 1000 psi to the end of the pressure holding period at 4950 psi.
[2] AE counts acquired by both sensors.
[3] AE counts acquired by the sensor at the valve-opening end. For cylinders 1 and 3, this sensor was close to the damaged site.
[4] AE counts acquired by the sensor at the dome end.

Table 4-2. Test Results in terms of AE Counts [1] for Cylinders 4-6.

Cylinder	Condition	AE counts [2]	AE counts [3]
4	Retired	730	3750
5	Retired	1620	13200
6	New	182	610

Notes: [1] AE counts shown in this table was acquired from 1000 psi
[2] Cumulative AE counts acquired at the end of the pressure hold of 2450 psi.
[3] Cumulative AE counts acquired at the end of the pressure hold of 2770 psi.

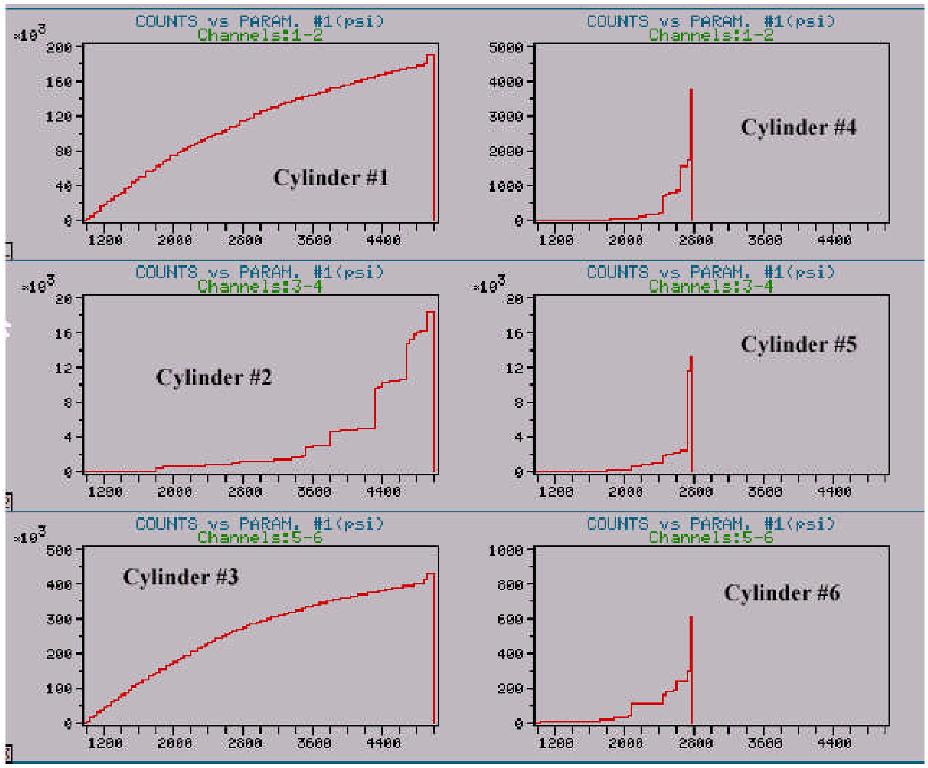

Figure 4-2. Cumulative AE counts vs. pressure for the test cylinders (note the different scales used in the graphs).

Discussion Of Results

Cylinders 1-3

The two damaged cylinders (1 and 3) showed a significantly higher level of AE activity than the undamaged one (2). Looking at the damaged cylinders, the total AE counts of Cylinder 3 (430,000) is more than twice that of Cylinder 1 (190,000). This is most likely due to the relative sensor location to the damage site, as the sensor at the valve-opening end of Cylinder 3 is closer to the damage site. However, for Cylinder 1 and 3, the AE counts acquired by the sensor at the dome end (far from the damage site) were still much higher than the AE counts acquired by both sensors on Cylinder 2. While Physical Acoustics Corporation have not yet determined an accept/reject criterion for these type of bottles, based on their previous testing with other carbon wrapped pressure vessels PAC indicated they would almost certainly call Cylinders 1 and 3 "Unacceptable" and recommend they be discarded. Cylinder 2 would be called "Acceptable", although again PAC presently does not have enough information available to confirm these calls.

Cylinders 4-6

While the two retired cylinders (4 and 5) produced more AE counts than the new one (6) at 2450 psi (110% of the service pressure), the difference is very small. At the higher test pressure, i.e. 2770 psi (125% of the service pressure), the three cylinders showed a larger difference in AE, however, PAC would still expect these cylinders to be acceptable for continued service. The overall AE activity of Cylinders 4, 5 and 6 are relatively low compared to Cylinder 2, which was an undamaged cylinder from the carbon wrapped cylinders

(Cylinders 1, 2, and 3). This is most likely related to the different cylinder constructions. However, cylinder loading history is also important, as any recent hydrostatic tests (normally to a pressure greater than 150% of the service pressure of the cylinder) or any other overpressure (greater than 110% of the normal operating pressure) would have an effect on the AE results. Based on these results, NTIAC recommends that acoustic emission be included in the follow-on work.

4.3 Thermography

The thermography feasibility studies were able to demonstrate surface and sub-surface flaw detection, as illustrated in Figures 4-3 through 4-5, which show both the conventional visual and the corresponding thermographic image of damaged cylinders.

Figure 4-3. Visual and thermographic pictures of Cylinder 1 (IL35248), illustrating the visibility of the impact damage on the composite cylinder.

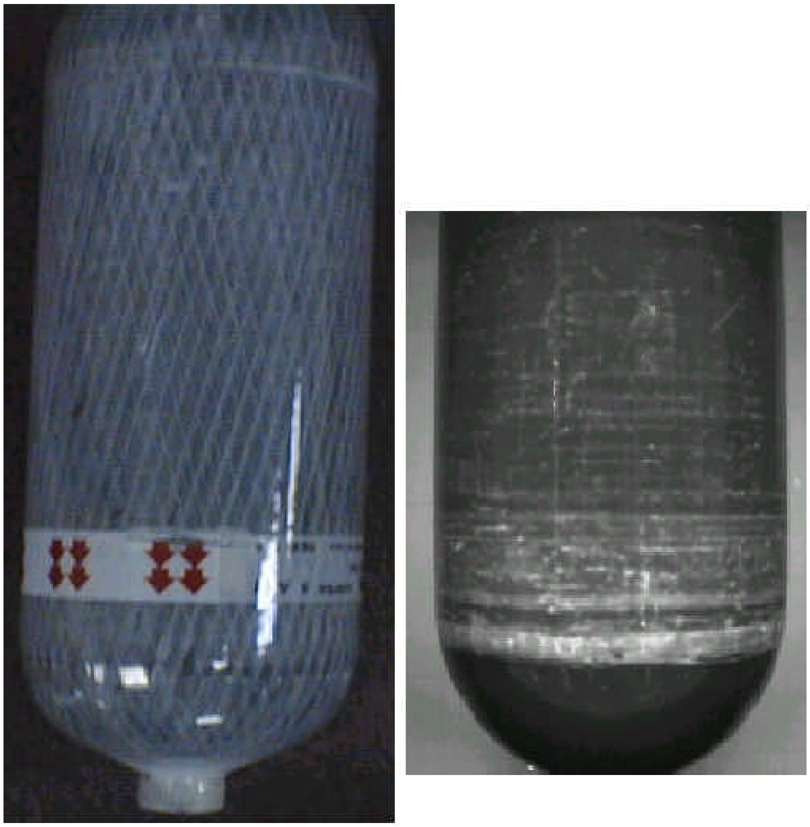

Figure 4-4. Comparing visible and thermographic indications of impact damage in Cylinder 3 (IL35250). In contrast with the thermograph of Cylinder 1, which has a similar severe impact anomaly, the impact damage in Cylinder 3 is not as clearly visible as in Cylinder 1.

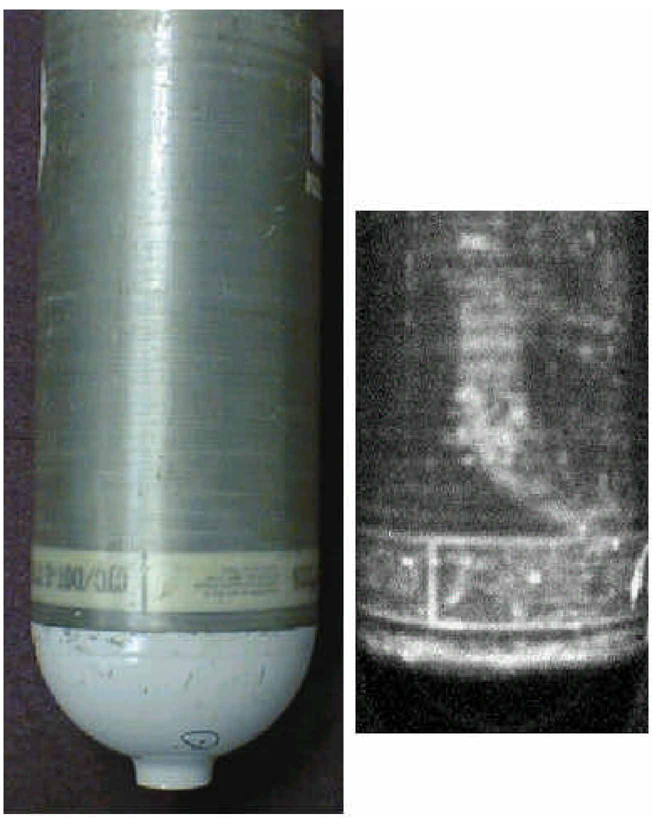

Figure 4-5. Comparing visual and thermographic images of one of the retired fiberglass cylinders. Although no damage is apparent in the conventional image, the thermograph clearly shows a sub-surface anomaly in the cylinder that would otherwise have escaped detection.

Interestingly, thermography was not able to detect the clearly visible impact damage on Cylinder 3 (Figure 4-4), while it was able to detect a similar level of impact damage in Cylinder 1 (Figure 4-3). The impact damage in Cylinder 3 was not as extensive as that in Cylinder 1, but was nonetheless severe. While acoustic emission testing did recommend scrapping Cylinder 3, thermographic testing would likely have passed the cylinder. In future studies, NTIAC suggests that both cylinders be burst tested to determine if the damage in Cylinder 3 would be sufficient to be condemned.

Thermal Wave Imaging reports that when using their standard system on filament wound designs, much of the heat is dissipated laterally along the wound filament, which often limits how deep into the part the system can see. Thermal Wave is currently upgrading their lab system in addition to looking at alternate methods of exciting the tanks/parts (i.e. other than light). As an aside, TWI notes that to better understand the reflectivity of the tanks to their light pulse, they looked at unpainted tanks with 2 different cameras before painting some of the tanks with easily removed flat black water based paint (which was quickly washed off). In addition, TWI feels confident about detecting surface/near-surface defects, but in follow-on work would like further information about the failure modes of the cylinders and depth requirements in order to tailor an inspection regimen.

The thermographic feasibility studies were also able to demonstrate detection of sub-surface anomalies, as illustrated in Figure 4-5. Although thermographic techniques were not able to achieve 100% penetration of the composite, NTIAC recommends that thermography be included in the follow-on work.

4.4 Ultrasonics

The original intent of the ultrasonics feasibility study conducted by Don Bray Engineering was to excite L_{CR} waves using the probe arrangement as shown by the angle beam wedge on the fiberglass tank (Figure 3-10 and Figure 4-6). The wedges were machined based on an assumed wave speed, which ultimately proved incorrect. As a result, an alternative approach was employed, in which a single source transducer with a pencil receiver looking at the wave patterns along radial lines from the source. This is a normal, longitudinal wave 5.0 MHz, ¼ inch diameter source probe with a 20 MHz pencil probe as the receiver (Figures 4-7 and 4-8). The plan was to trace the arrivals along radial lines from the source, which would allow for the examination of the ultrasonic properties of the tanks.

Figure 4-6. Close-up picture of the angle beam wedge on tank

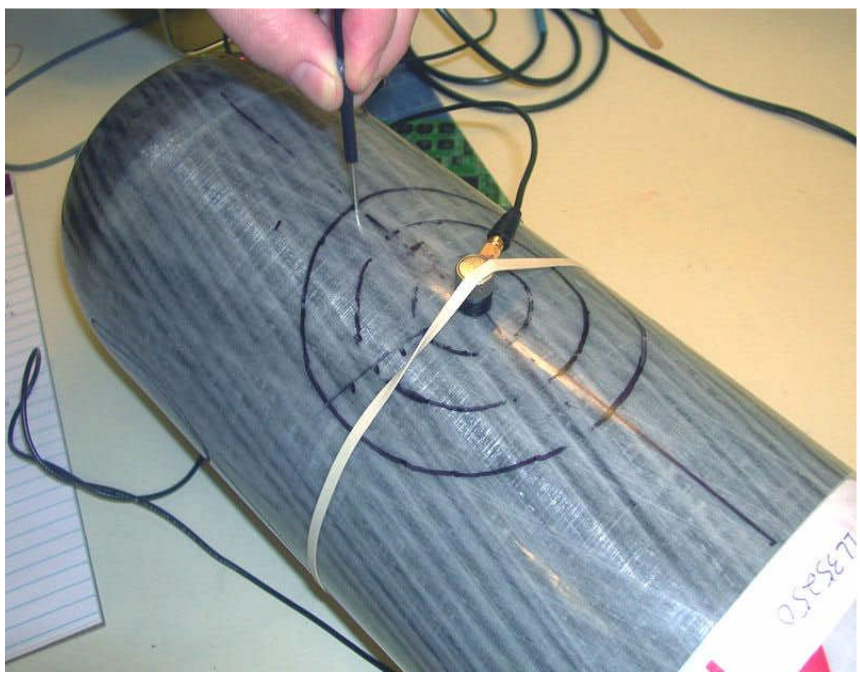

Figure 4-7. Graphite epoxy tank showing source and receiver probe placements.

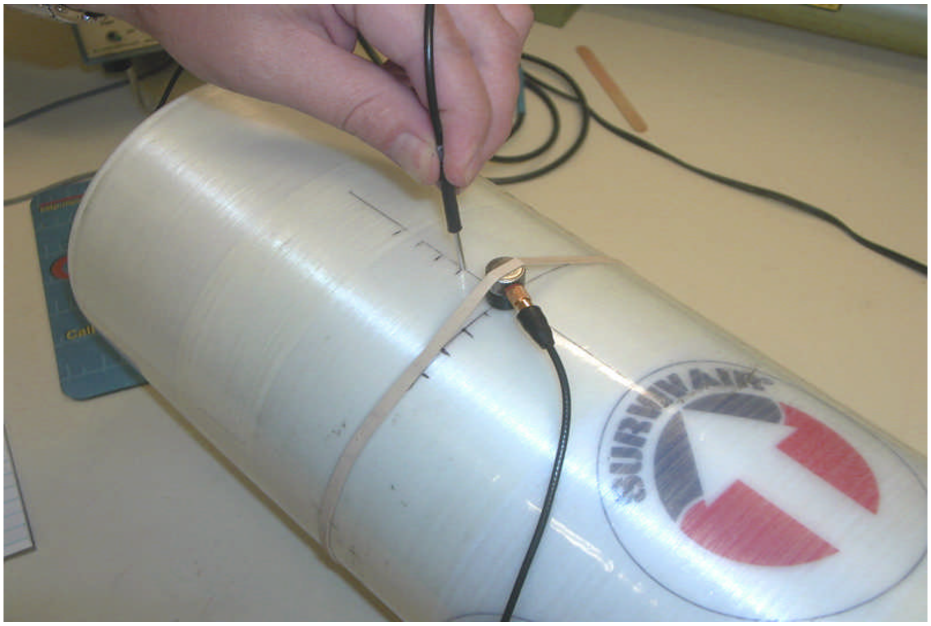

Figure 4-8. Fiberglass tanks showing source and receiver probe placements.

Table 4-3. Summary of the ultrasonic properties calculated for the composite cylinders.

Cylinder	Time Difference (ms)	Velocity (m/s)	Likely Primary Wave Path
2	7.9 – 3.3	6522	Longitudinal in aluminum
2	33 – 27	3300	Longitudinal in Graphite epoxy or shear in aluminum
3	8.4 – 3.6	6250	Longitudinal in aluminum
3	21 – 14.2	4417	Longitudinal in graphite epoxy
3	30 – 26	7500	Unknown
5	9.1 – 4.2	6122	Longitudinal in aluminum
5	23 – 13.6	3191	Longitudinal in fiberglass or shear in aluminum
5	29 – 21	3750	Longitudinal in fiberglass or shear in aluminum

Based on these studies, Don Bray Engineering was able to demonstrate ultrasonic propagation through the composite layer, and from there to produce a table of ultrasonic velocities and likely wave paths as summarized in Table 4-3. Figure 4-9 illustrates the wave paths suggested by the study.

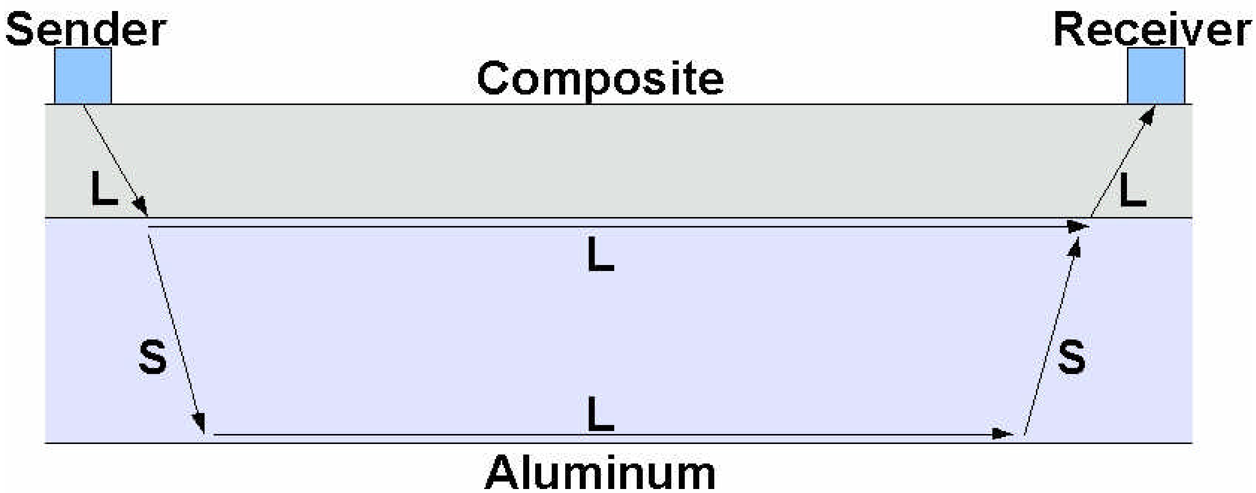

Figure 4-9. Suggested energy paths determined during the ultrasonics feasibility study, showing the propagation of both shear (S) and longitudinal (L) ultrasonic waves through the cylinder.

Damage assessments were not possible with these measurements. Although ultrasonics has been shown to be able to propagate through the composite layer to achieve 100% penetration, the realities of composite cylinder construction complicates ultrasonic inspection. Specifically, tolerances as far as composite layer thickness, fiber orientation, etc. are more relaxed than in other composite structures (e.g. as used in aerospace), which proves problematic for determination of required ultrasonic inspection parameters. This is evidenced by the difficulties in estimating the average wave velocity in the current studies. To employ ultrasonic inspection techniques in the inspection of the composite gas cylinders, therefore, further characterization of the cylinders' ultrasonic properties would be required before any UT system could be fielded.

5.0 CONCLUSIONS

NTIAC conducted a literature review for the inspection of composite compressed gas cylinders. During the review, candidate NDE technologies were evaluated for feasibility based on the state-of-the-art literature in inspection of composites and composite cylinders. Several promising technologies were identified, based on the literature, and down-selected for the subsequent initial feasibility tests.

The down-selected NDE inspection techniques were evaluated for feasibility by conducting an initial test inspection of a set of six composite cylinders, three carbon and three fiberglass, in a variety of conditions. NTIAC commissioned several NDE service providers to conduct a preliminary inspection of a set of six composite gas cylinders. The purpose of the preliminary inspections was to establish the feasibility of the inspection technique to quantitatively inspect composite cylinders in the field.

Based on the findings and conclusions of the study participants, NTIAC recommends that the following inspection techniques be studied further in follow-on work:

- **Acoustic Emission**

- **Thermography**

Both techniques were able to demonstrably accept and reject cylinders based on their assessed damage conditions, even with the relatively brisk inspections conducted during this investigation. Of the two, acoustic emission is the more developed technique in terms of approaching fieldability, primarily due to the efforts of Physical Acoustics in similar projects.

Thermography was shown to be able to detect surface and sub-surface flaws, although it would not be able to globally inspect the composite (i.e. achieve 100% penetration). In addition, thermography did not detect a substantial impact damage flaw that was clearly visible, which may indicate some potential issues with future deployment. NTIAC recommends that the cylinder in question be burst-tested in follow-on work to determine whether the damage was sufficient for condemnation.

Ultrasonic inspection, although able to show propagation through the composite and even through to the aluminum, would require significant further development before a field-ready UT system could be deployed. In particular, this is due to the looser tolerances employed in the composites used in the composite gas cylinders, which may exhibit a wide range of ultrasonic properties. Most notably, the thickness of the composite layer can vary from cylinder to cylinder, and would complicate ultrasonic inspection without a complete system development project. In short, although potentially an applicable technology, ultrasonics would require substantial R&D efforts.

NTIAC recommends that future efforts be directed to further downselection of the applicable technologies. This would be accomplished by conducting a full "round-robin" inspection of a set of cylinders with known flaws and conditions, similar to the highly successful study NTIAC conducted with downselecting an inspection regimen for aluminum gas cylinders. In that study, the cylinders were nondestructively inspected and then the results were correlated with the destructive analysis of a subset of the cylinders. In the current efforts, NTIAC believes that an appropriate approach is to burst test the inspected cylinders and compare the results with the nondestructive inspections.