ATK Development of a Practical Nondestructive Examination for Detection and Evaluation of an Impact Damage in *Fully Wrapped Carbon-Fiber Reinforce Aluminum-Line Cylinders (CFFC)*

Final Report –Phase I

22 August 2008

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Contents

1.0 BACKGROUND

The Office of Hazardous Materials Safety, under the U.S. Department of Transportation's Pipeline & Hazardous Materials Safety Administration (DOT/PHMSA), has the responsibility of assuring the safe shipment of high-pressure gas cylinders that are manufactured in accordance with 49 CFR and special permits. The majority of the composite cylinders used for transportation of high-pressure gases are manufactured in accordance with DOT specification FRP (Fiber-Reinforced Polymer) and CFFC (Carbon Fiber Reinforced Cylinders). In recent years, the use of composite cylinders has become more widespread in breathing apparatus and industrial gas service. PHMSA has granted several special permits for the manufacture and use of composite cylinders that are authorized for transportation of various compressed gases; including hydrogen at service pressures not exceeding 6,500 psi and a maximum water capacity of 200 pounds (24 liters).

These cylinders are required to undergo a hydrostatic test and a visual inspection every five years. However, PHMSA is aware of the limitations of this method in the detection of certain types of defects and damage that may affect the integrity of composite cylinders over time. Therefore, reliable Non-Destructive Examination (NDE) method(s) that will increase the accuracy in the detection of critical flaws are required. The creation of new testing methods would be of particular use considering the numerous public requests for composite cylinder life extensions beyond the current 15-year limit. Unfortunately, without an NDE method that can more accurately assess damage caused during normal usage, such life extensions may not be possible. For these reasons, the current effort to evaluate composite cylinders by an effective NDE method is proposed. This current work statement has culminated as a follow up to the DOT sponsored feasibility study in which several potential NDE techniques were reviewed and assessed for their effectiveness at detecting defects in carbon composite high-pressure gas cylinders.

2.0 LONG TERM OBJECTIVE

The objective of this effort is to determine the quantitative capability of an NDE technique (e.g. acoustic emission) to accurately detect and assess operational impact damage in composite cylinders. The knowledge gained from this effort will then be used to design an optimal testing procedure that will subsequently be recommended for use in composite cylinder re-qualification. In support of this long-term objective, the following items are the staged milestones that must be crossed before a field-ready re-testing technique could be implemented:

- Determine critical flaw types and sizes.
- Develop an NDE method that is capable of detecting and quantitatively measuring a flaw produced by an impact. The NDE data must be reproducible and clearly distinguishes the following:
    - A new cylinder with no impact damage.
    - A cylinder with moderate (acceptable) impact damage.
    - A cylinder with severe (which may cause failure before the next re-qualification) impact damage
- Verify the NDE for use at field for re-qualification of composite cylinders.

3.0 SPECIFIC OBJECTIVES - Phase I

3.1 Classification of Applied Impact Damage

i. Assess and document the types of impact damage to which a composite cylinder may be subjected and the scenarios under which each type would likely occur.
ii. Obtain additional information relating to impact damage.
iii. Identify key parameters that must be included in modeling and testing.

3.2 Trial Impacting

i. Perform trial impact testing on 15 CFFC's to determine the damage encountered during normal field usage.
ii. Document the following:
   - NDE procedures developed
   - Values for the key parameter set (e.g. energy, velocity, mass, etc…)
   - Visual assessment of the cylinders with onset damage
iii. If necessary, perform an evaluation of the liner to determine if impact damage to it plays a significant role in the reduction of residual strength.
iv. Correlation between impact and selected energies.

3.3 Correlation between Destructive Impact Damage and NDE Data

i. Perform NDE on impact sites
ii. Thermally de-ply the damage zone to evaluate the extent of fiber damage
iii. Establish preliminary correlation between NDE data and the imposed damages

3.4 Impact Effects Modeling

i. Determine the extent of material property data needed (lamina/laminate) for Finite Element Modeling and perform any necessary testing in support of this need

3.5 Structural Testing

i. Establish testing method/procedure
ii. Determine baseline for undamaged cylinder strength
iii. Characterize acoustic emission (AE) response of undamaged cylinders
iv. Characterize AE of damaged cylinders tested
v. Establish baseline AE measurement for the damaged and undamaged cylinders

4.0 PROGRESS

4.1 Classification of Applied Impact Damage

Assess and document the types of impact damage to which a composite cylinder may be subjected and the scenarios under which each type would likely occur.

Unfortunately our attempts to gather information about likely damage scenarios were unsuccessful. Carleton declined the opportunity to share their database with us. Information obtained in discussions with Carleton personnel was qualitative at best. We do know that cylinders frequently come in contact with hard objects during routine handling. Examples include a drop from the height of a truck or cylinder carrier. The impacts, if hard enough can cause visible scuffmarks, delaminations and fiber breakage within the composite over wrap and dents within the aluminum liner. The magnitudes of these damage types however are not well documented. We were not able to find any information that defined a damage level that would cause a cylinder to fail during its life cycle.

Lack of information on damage levels is critical for designing an effective test program. Since a limited number of cylinders were available for the Phase I work the impact testing must make efficient use of available assets. Given these constraints we decided to use a couple of cylinders to induce several levels of damage before designing the main test program. Damage level information (determined from NDE and deply methods) coupled with ATK's prior experience with damage effects testing thus became the basis for the Phase I test matrix that is describe later.

Obtain additional information relating to impact damage.

No additional information was obtained.

Identify key parameters that must be included in modeling and testing.

Key parameters that must be included in impact event modeling and testing include the following:

- Impactor shape and hardness
- Impactor mass
- Impactor velocity
- Impactor angle of incidence
- Cylinder design (materials, composite layup, liner type, etc.)
- Cylinder support condition
- Cylinder pressure at time of impact
- Cylinder age (number of pressure cycles)

Determining the effects of all these parameters and their various combinations makes impact test programs complex and costly. Our experience with other impact test programs has taught us which parameters are most important however. The Phase I impact test matrix was designed to provide preliminary assessments of damage effects over a realistic range of damage levels. This approach allowed us to focus our primary effort on the NDE damage discrimination method. Phase I impact test parameters were selected as follows:

- Impactor shape - 6 inch diameter hemisphere, steel
- Impactor mass – 35 to 100 lbm
- Impactor velocity – low velocity, 70-100 inch per second
- Impactor angel of incidence – normal
- Cylinder design – Carleton composite overwrapped, aluminum linear
- Cylinder support condition (full cylinder) – wooden saddle
- Cylinder support condition (half cylinder) – steel plate, picture frame support
- Cylinder pressure during impact – ambient
- Cylinder age - virgin

4.2 Trial Impacting

Perform trial impact testing on 15 CFFC's to determine the damage encountered during normal field usage.

One of the first tasks of the Phase I effort involved creating a specific test matrix so that available cylinders could be used efficiently. Each cylinder in the test matrix had a specific objective. The objectives are designed to determine things such as cylinder design, create a range of levels of damage levels, evaluate NDE methods, determine cylinder undamaged and damaged strength, and to measure acoustic emission response during strength testing for undamaged and damaged cylinders. The matrix was intentionally made smaller than the number of available cylinders so that a second round of testing could be performed if necessary. The Phase I test matrix is shown in Table I.

Since we were unable to obtain detailed design information from Carleton we choose to dissect one cylinder to determine details of the cylinder design. This approach provided information about the liner configuration and lay up of the composite over wrap. Figure 1 shows a photograph of the cut cylinder. Note that the both glass and graphite plies are visible along with the liner profile. Although we can see the basic design these data are not enough to perform detailed finite element modeling. Laminate mechanical properties are needed.

Table I – Phase I Test Matrix

Serial	Damage Condition	AE	Cut for Inspection/ Thermal Deply	Burst	Plan	Pre Impact NDI
6109-52085	Damaged	No	No	No	Cut bottle to determine design features and materials	Yes
6109-52086	Undamaged	Yes	No	Yes	Burst as Control	No
6109-52075	Undamaged	Yes	No	Yes	Burst as Control	Yes
6109-52078	Undamaged	Yes	No	Yes	Burst as Control	Yes
6109-52082	Damaged	No	Yes	No	Impact 1/2 bottle after cutting. Other 1/2 used for NDI baseline. Thermal deply (4) impact locations	No
6109-52079	Damaged	No	Yes	No	Impact 1/2 bottle before cutting. Cut in half and impact other half with same energy. Impact should be just enough energy to dent aluminum. Investigate NDI from inside. Thermal deply all (8) impact locations	No
6109-52089	Damaged	Yes	No	Yes	Impact with just enough energy to dent aluminum, NDI and burst	Yes
6109-52090	Damaged	Yes	No	Yes	Impact with enough energy to damage composite, NDI and burst	Yes
6109-52093	Damaged	Yes	No	Yes	Impact with energy level well above standard drop test level	Yes

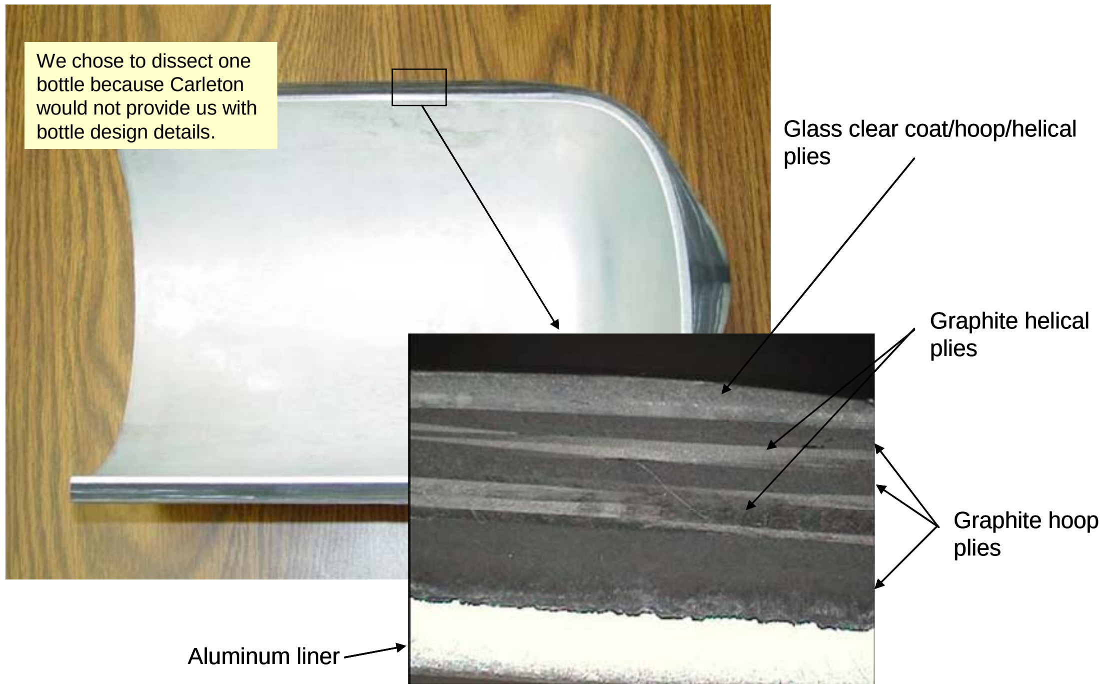


Figure 1. Cut cylinder shows laminate and liner configuration

Cut cylinders were used to perform a preliminary round of trial impact tests. These tests were designed to identify the damage modes that result from progressively higher energy levels. We hoped to span the damage levels that typically occur in fielded cylinders. We do not yet know if we were successful. Cut cylinders provided an opportunity to measure damage (dent) in the liner aluminum liner. We were particularly interested is seeing how the dent shape varied with increasing impact energy.

Document the following: NDE procedures developed, values for key parameters set, and visual assessment of cylinders with onset of damage.

NDE techniques performed an important role in the Phase I test program to provide information about damage states that result from impact events. Damage level measurement helped guide the experimental effort whose goal as to provide a wide range of damage levels. A primary goal was to establish the relationship of damage level and impact energy. This information was used to select damage levels for the strength test cylinders.

Damage modes that are important in determining cylinder strength include delamination location and size and level of fiber breakage. The damage to the aluminum liner is probably also important but we have no prior experience with the effects of this damage mode. We selected a phased array ultrasonic technique to accurately measure delamination sizes. This decision was based on work from other impact damage programs.

The phased array technology provides fast, high spatial resolution data. Phased array ultrasonic scans performed two primary functions. First, it verified that strength test cylinders had no pre-existing damage prior to testing. Second, each impact site was scanned to provide delamination size, location, and depth. Figure 2 shows a photograph of three impact sites on cylinder 52082. The impact sites are distinguishable by the light colored regions. The white rectangular box is the scan area for a phased array scan. Figure 3 shows the phased array C-scans two impact sites. Note that the C-scan images clearly show lateral extent of the damage. The B-scan images in Figure 4 show depth of the delaminations. It should be noted that some stacked configuration of delaminations can't be imaged completely due to blockage of sound transmission.

Visual examination of the cylinders provided a secondary method for determining delamination size and location. The visual method however is limited to delamination within the semi-transparent fiberglass layer. Figures 5 and 6 show visible impact damage delaminations that occur between the hoop and helical layers of the glass over wrap. This damage mode is the first to occur during an impact event. A visible delamination will therefore be a reliable indicator that an impact event has occurred. Its size and shape cannot be used to assess damage deeper within the laminate however.

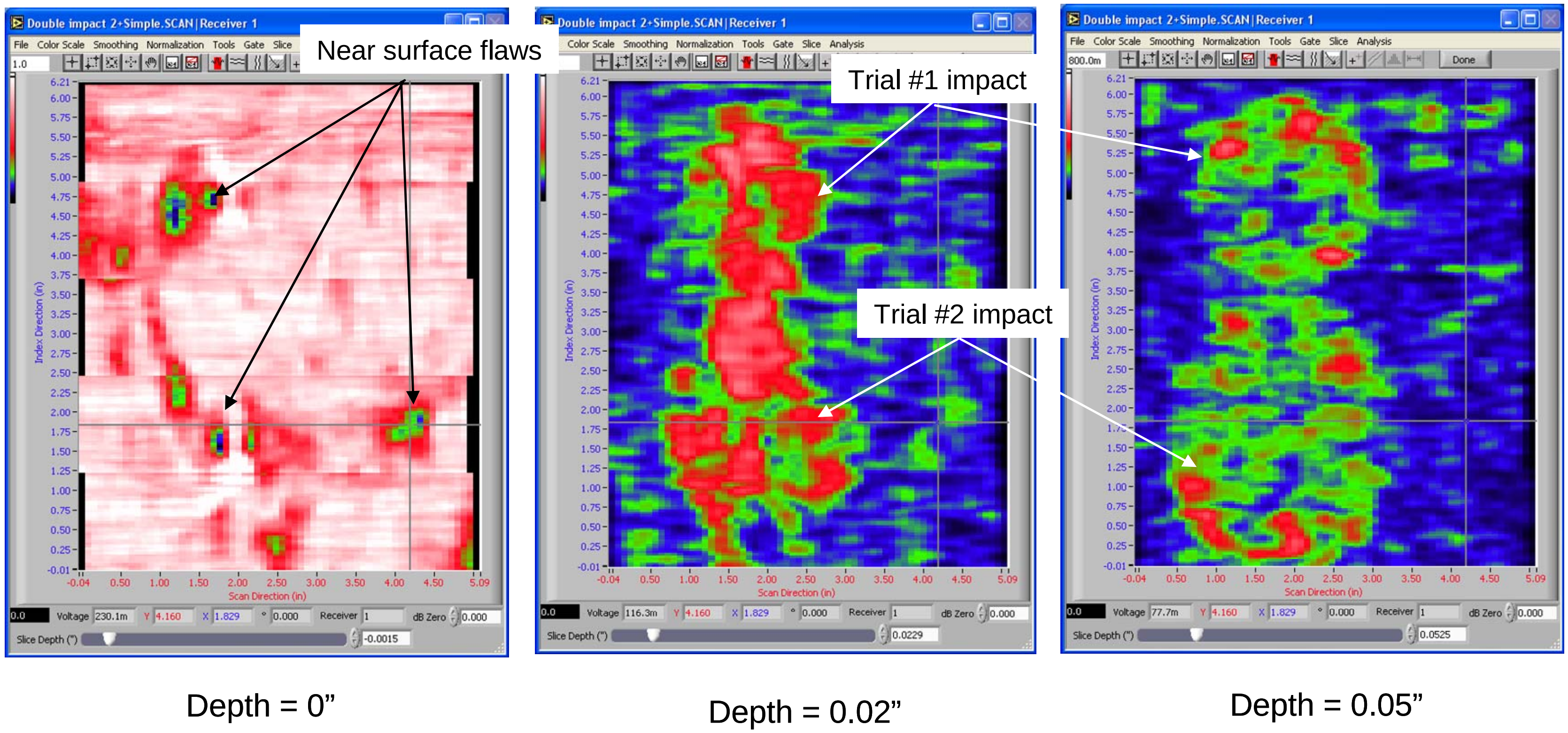
Since there is currently no reliable NDE method for measuring fiber breakage within a ply this damage parameter was measured on select samples with a destructive method known as deplying. The deply method involves cutting out the impact site and baking off the resin matrix. This process leaves the individual composite plies in tact so that they can be evaluated and photographed. Figure 15 shows a photograph of a deply sample. Note that ply cracks are visible in both hoop and helical layers. Measuring crack lengths for each ply allows one to construct a 3 D location map for all cracks.

Perform an evaluation of the liner to determine if impact damage to it plays a significant role in the reduction of residual strength.

The role of the liner is important when considering how a composite over wrapped cylinder responds to an impact event. (We expect that the damage state will be quite different for a cylinder with a plastic liner for an equivalent impact event.) If the composite over wrap deforms enough during an impact the aluminum liner will permanently dent. This dent will disrupt the normal stress transfer that occurs

Figure 2. Scan zone for two impact sites

C-scan Images At Different Depths



Wavespeed = 61,900 in/s

Figure 3. C-scan images for two impact sites

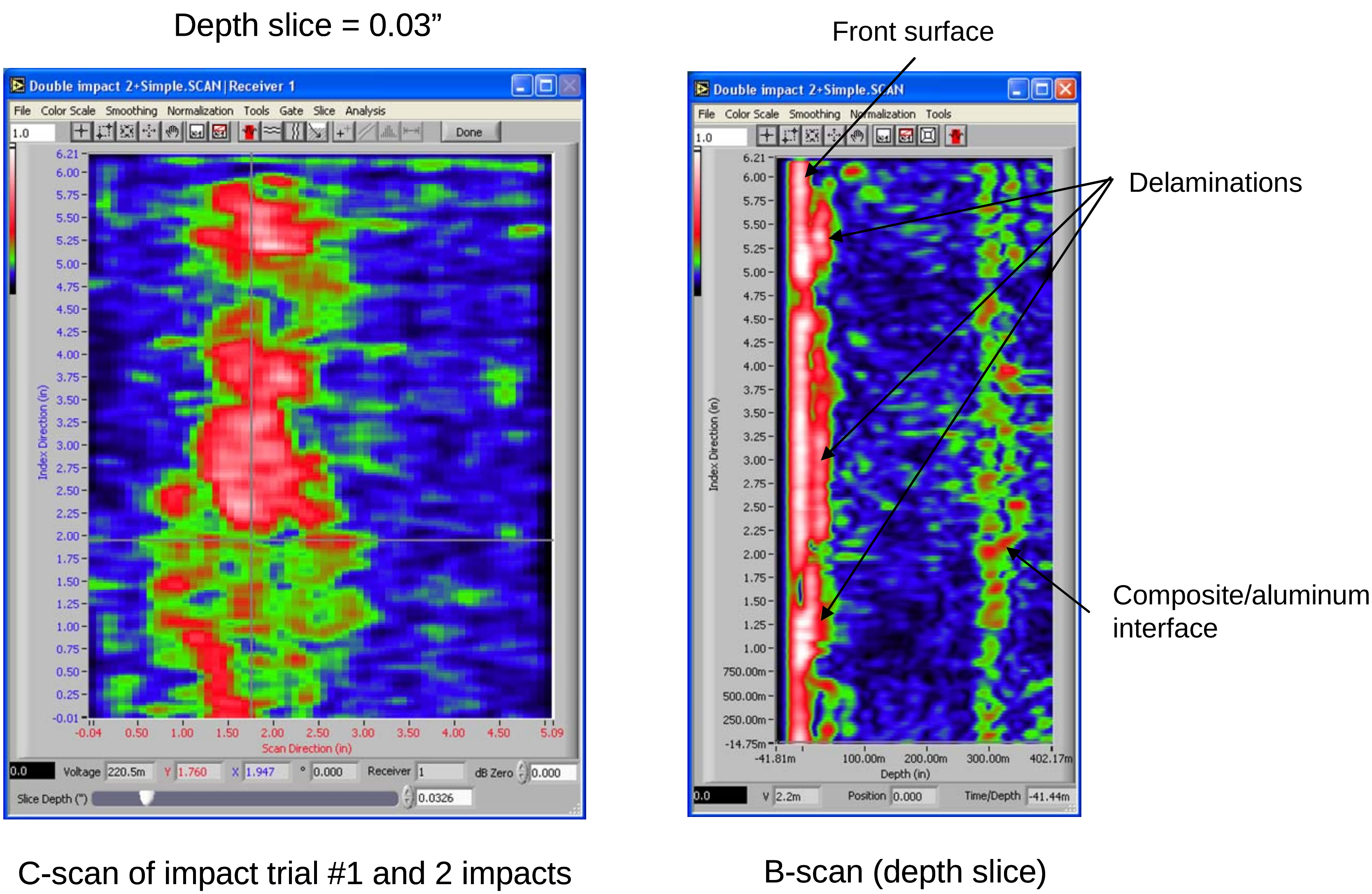


Figure 4. B-scan images show delamination depth

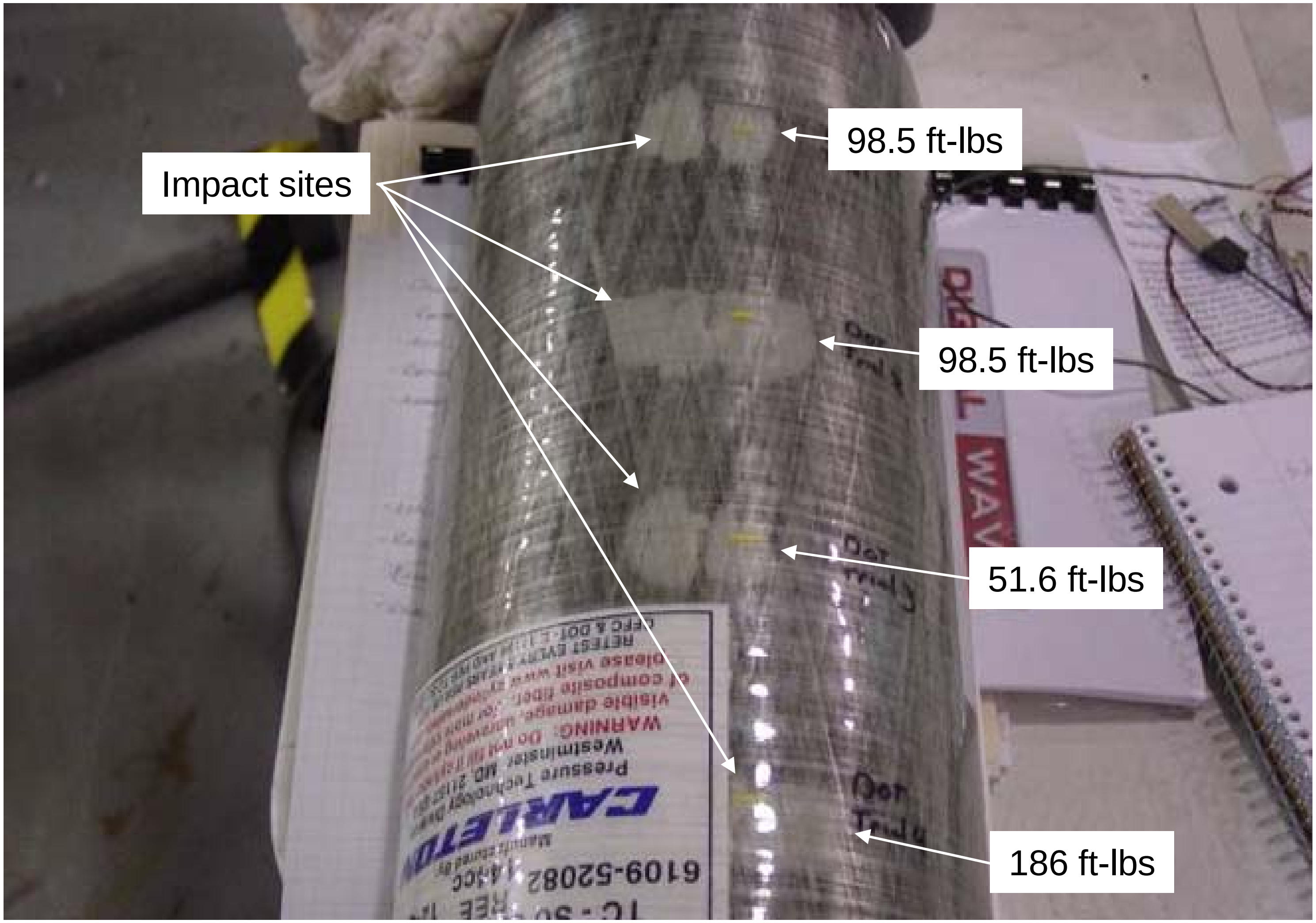


Figure 5. Visible delaminations from four impact sites, Impact energy is also shown

Figure 6. Visible delaminations are easy to size

between the liner and it's over wrap while the cylinder is pressurized. The effect of the dent on cylinder performance during cyclic loading is not clear. The other reason the dent is important is because its creation absorbs impact energy. This absorption most likely reduces the amount of damage in the composite over rap.

We intentionally chose to impact some cut cylinders so that the liner could be visually inspected. Dent depths and profiles were measured for all cut cylinder samples that were impacted. Figure 7 shows a photograph of one such impacted cylinder half segment. Note that the dents have smooth profiles. Expectedly we found that dent depths correlate with impact energy. Figure 8 shows this correlation. This observation suggests that dent measurement might be an effective means of nondestructively determining approximate damage levels. A dent scanner could be developed to exploit this idea.

Correlation of impact damage and with selected energies.

It is well known that impact damage levels correlate with impact energy because the creation of damage is a fundamental mechanism that absorbs this energy. The correlation for the Carleton cylinders tested so far is shown in Figure 9. Note that this correlation is with the measured delamination size as determined from the ultrasonic scans. Delaminations however are not the most critical form of damage in a pressure vessel. Our experience is that fiber breakage is the most important damage mode. Figure 9 shows the relationship between impact energy and the number of hoop plies damaged. Note that hoop tow damage begins at around 20 ft-lbs impact energy. Above this level to around 100 ft-lbs the relationship appears to be approximately linear. We only impacted two cylinders, 52082 and 52093, above the 100 ft-lb energy level. Fiber breakage on the 52082 half cylinder (182 ft-lbs) was extreme and could not be easily quantified. Fiber breakage on cylinder 52093 (245 ft-lbs) is unknown because it was pressurized to burst.

4.3 Correlation Between Destructive Impact Damage and NDE Data

Perform NDE of Impact Sites.

All impact sites, with the exception of the 245 ft-lb cylinder site, were inspected with both phased array and visual methods. In addition, cut cylinder liner dents in were measured with a micrometer device. Phased array scan results are shown in Figures 10 for cylinder 52079 and 11for cylinders 52089 and 52090. Visual data are shown in the photographs of Figures 12 and 13 for cylinder 52079 and 14 for cylinder 52093. Dent sizing data are listed in Table II.

Thermally deply the damage zone to evaluate the extent of fiber damage.

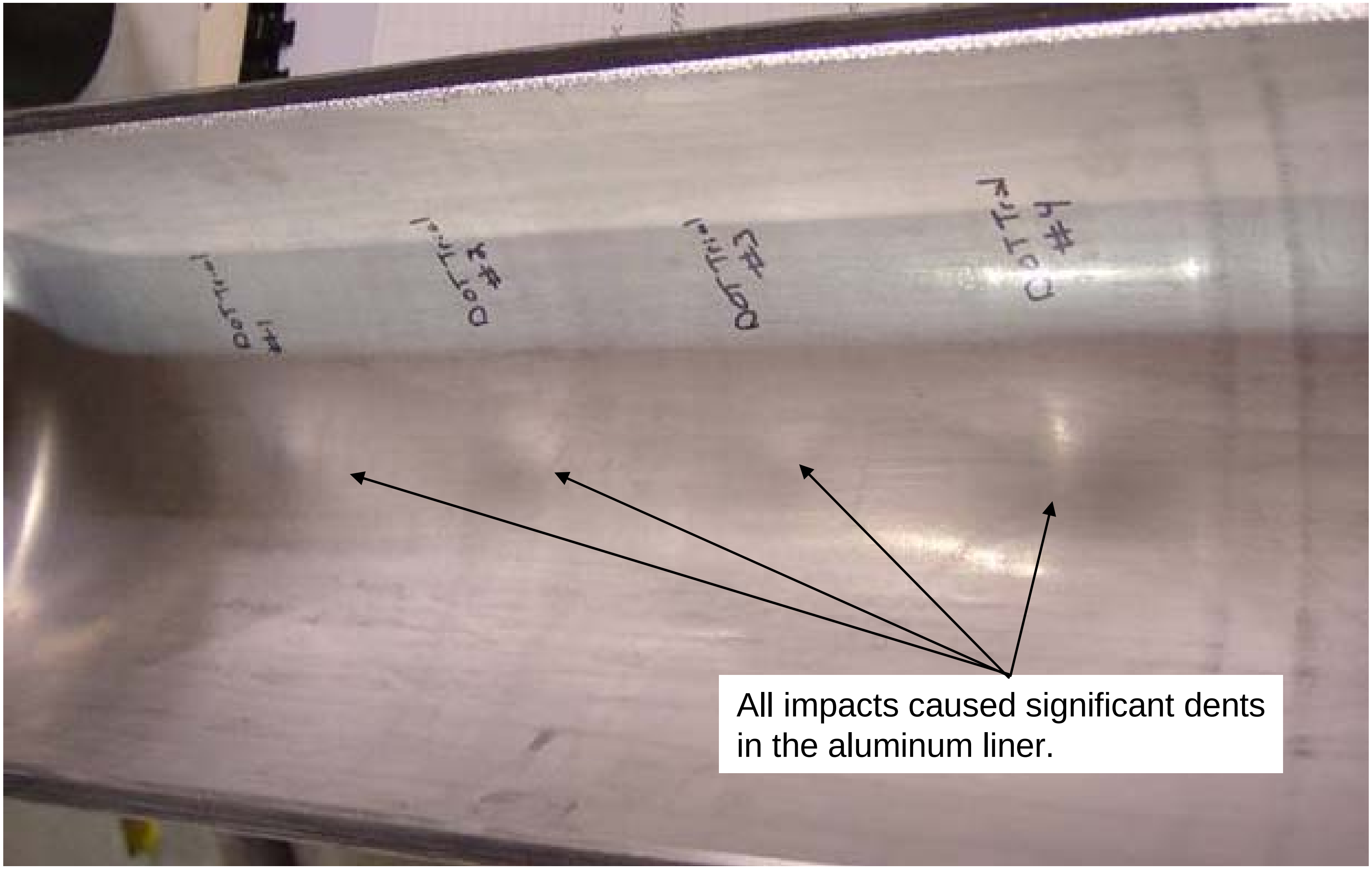


Figure 7. Photograph shown liner dents from several impacts

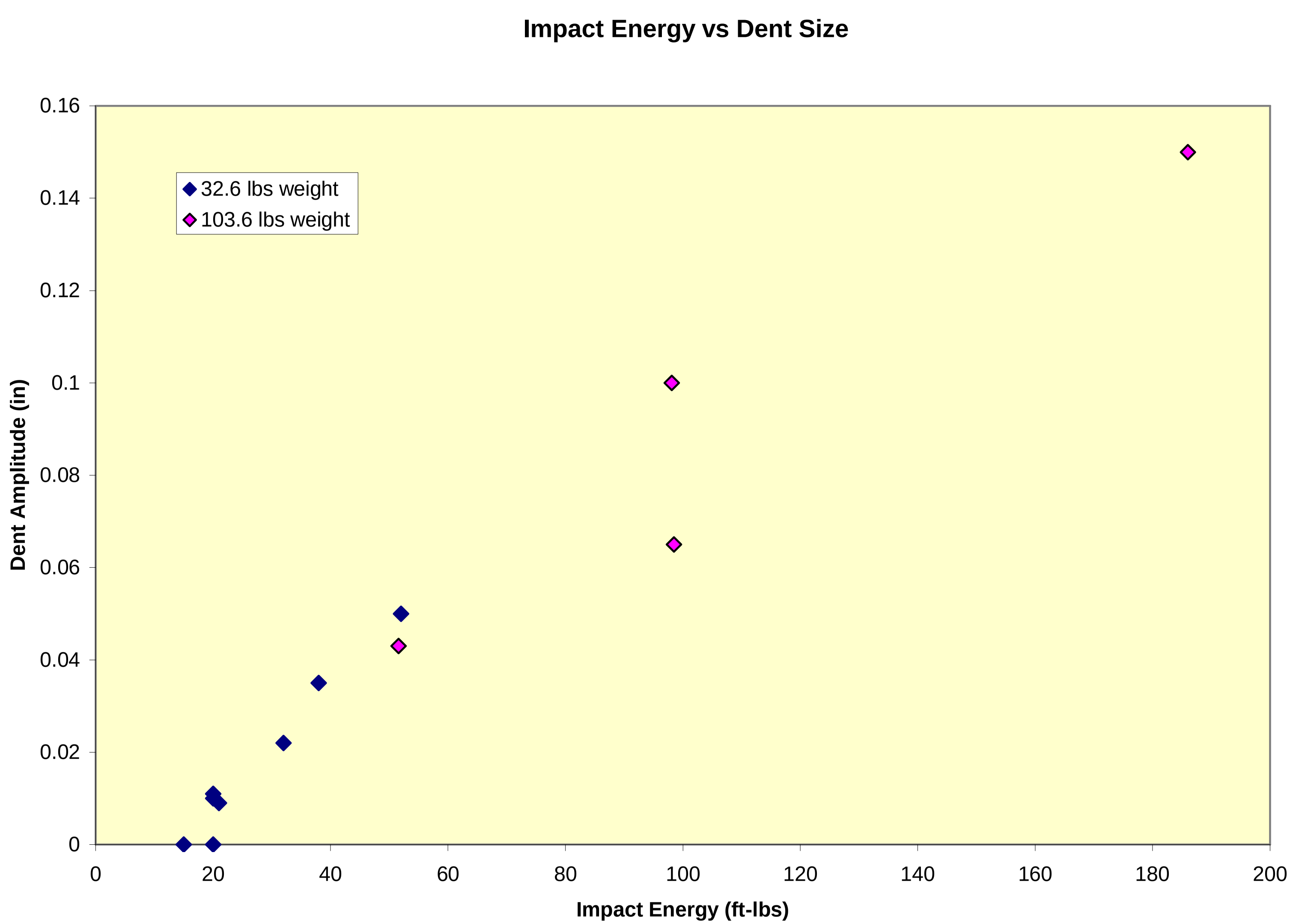


Figure 8. Dent size correlation with impact energy

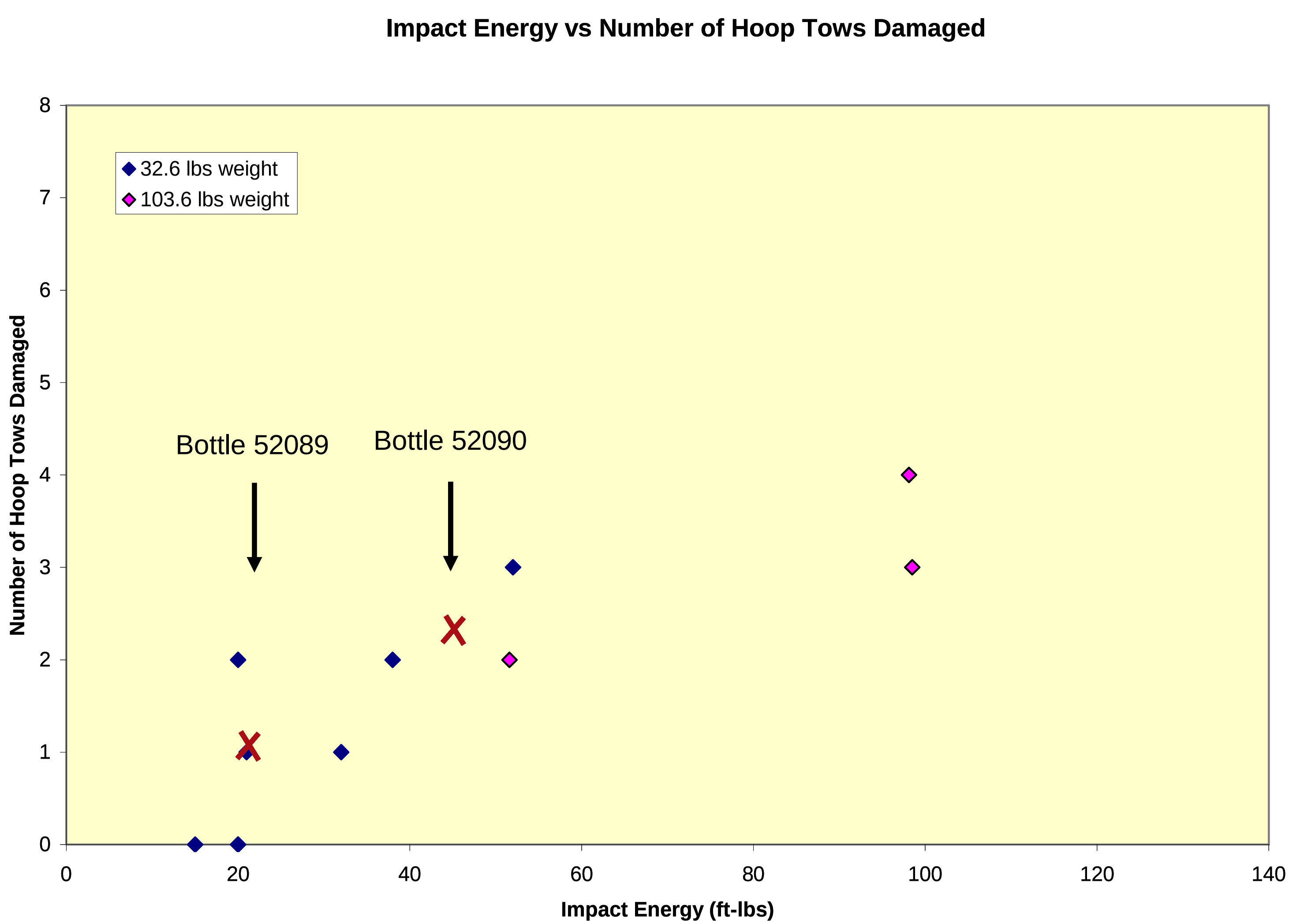


Figure 9. Hoop crack correlation to impact energy

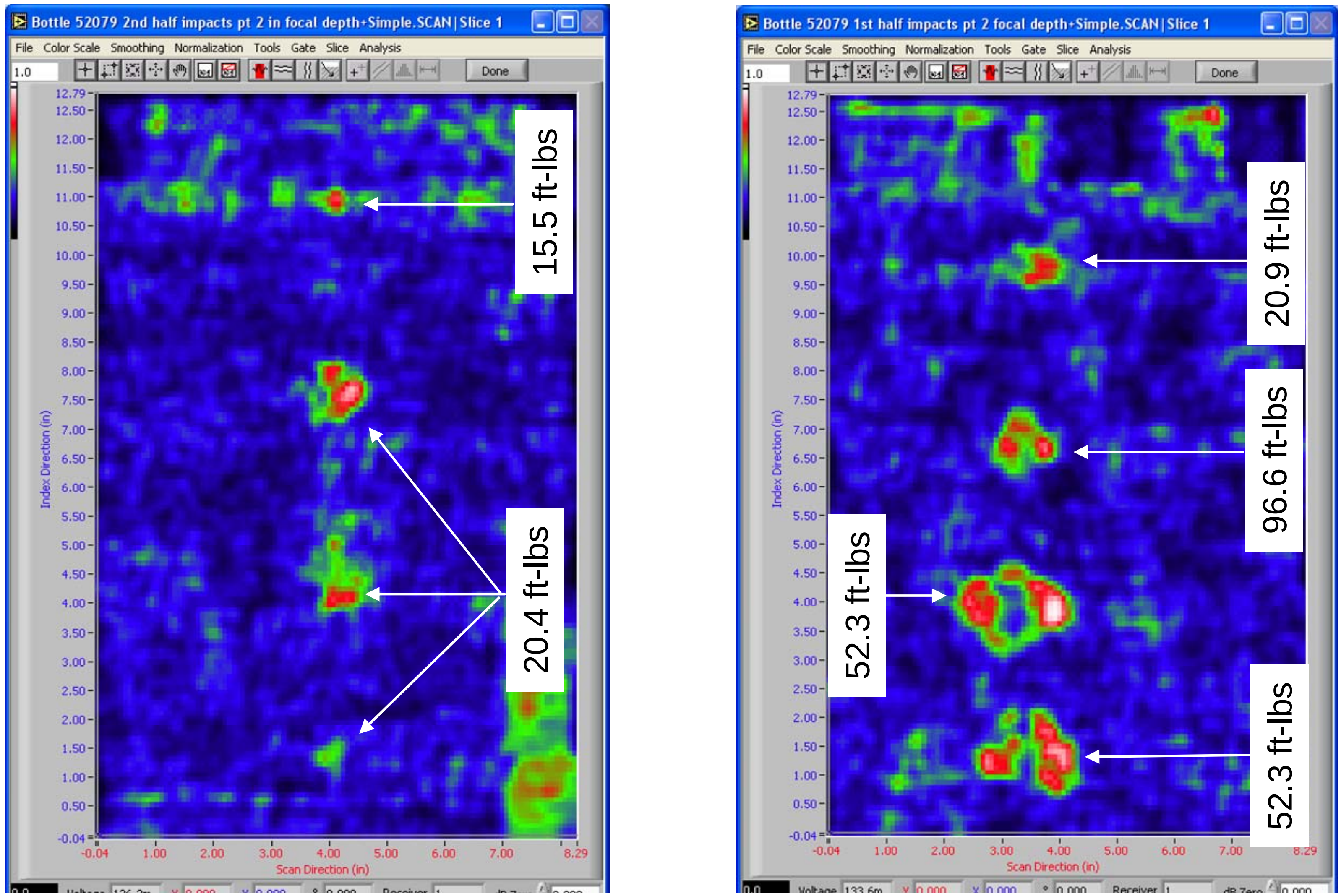
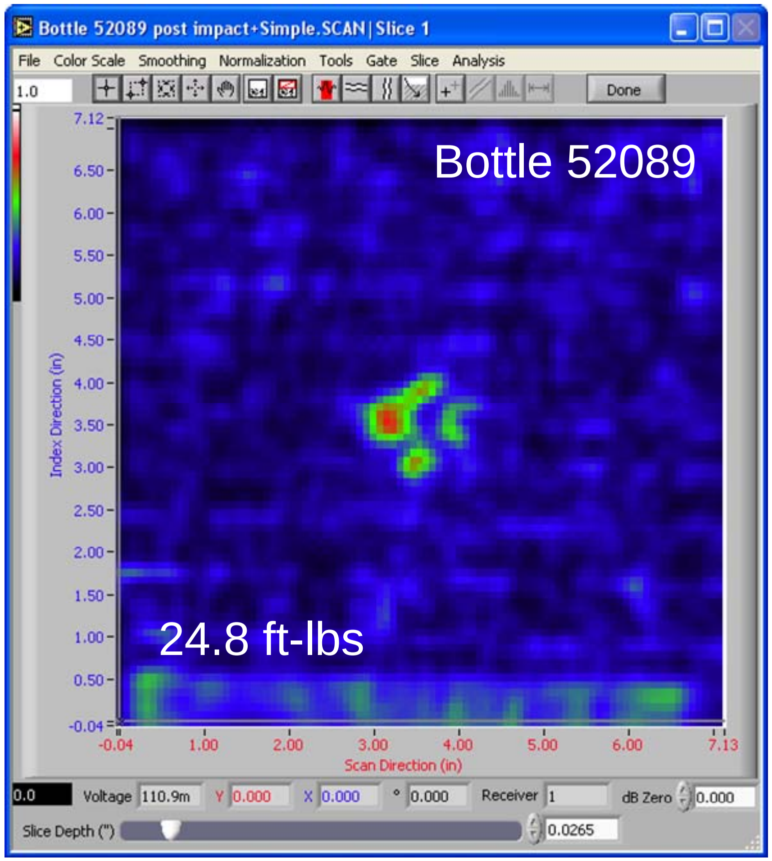


Figure 10. Phased array scan C-scan images for cylinder 52079



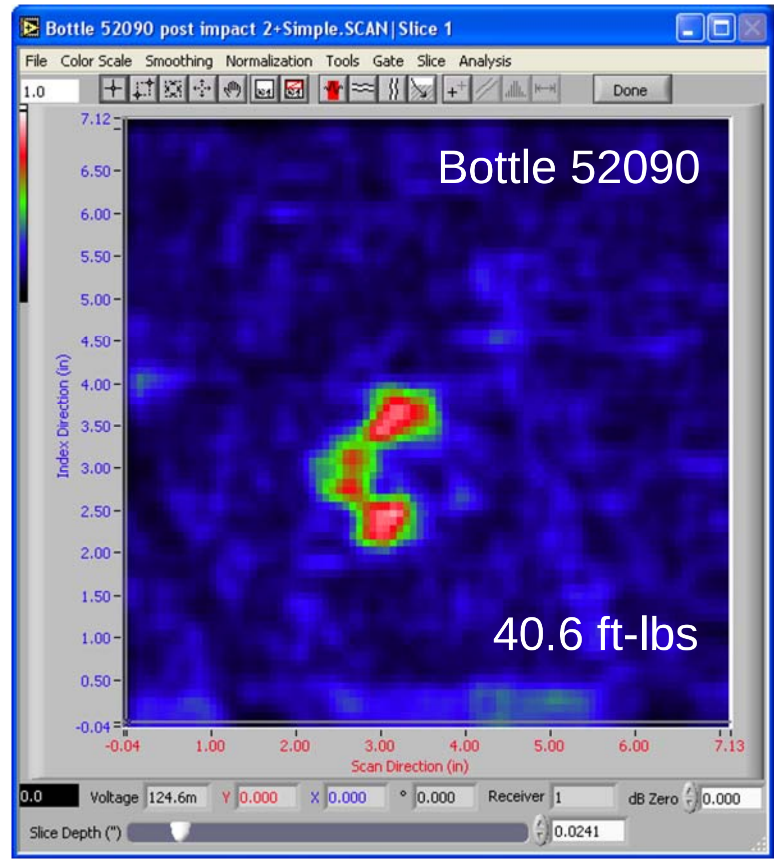


Figure 11. Phased array C-scan images for cylinders 52089 and 52090

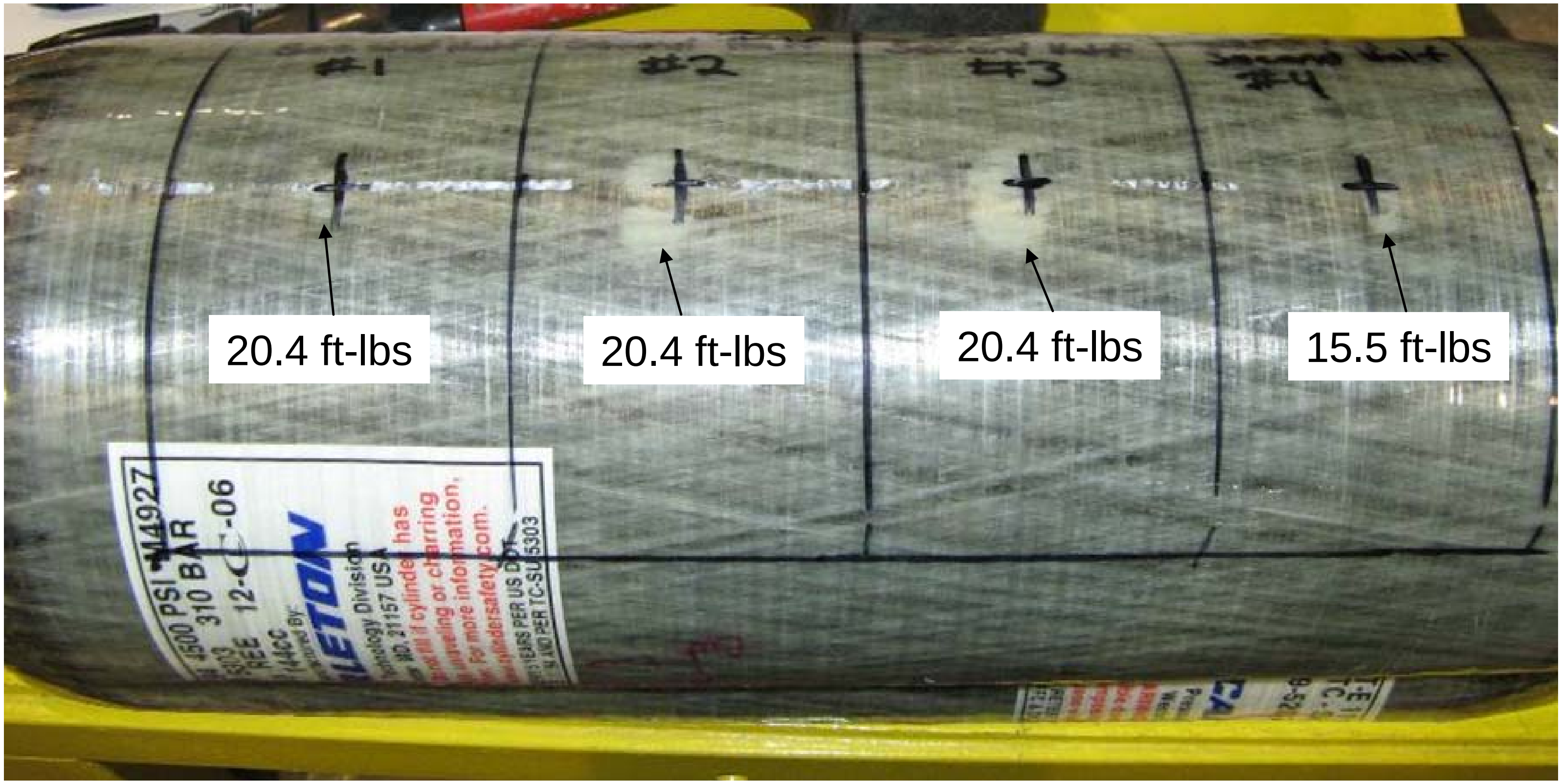


Figure 12. Photograph of impact sites for cylinder 52079

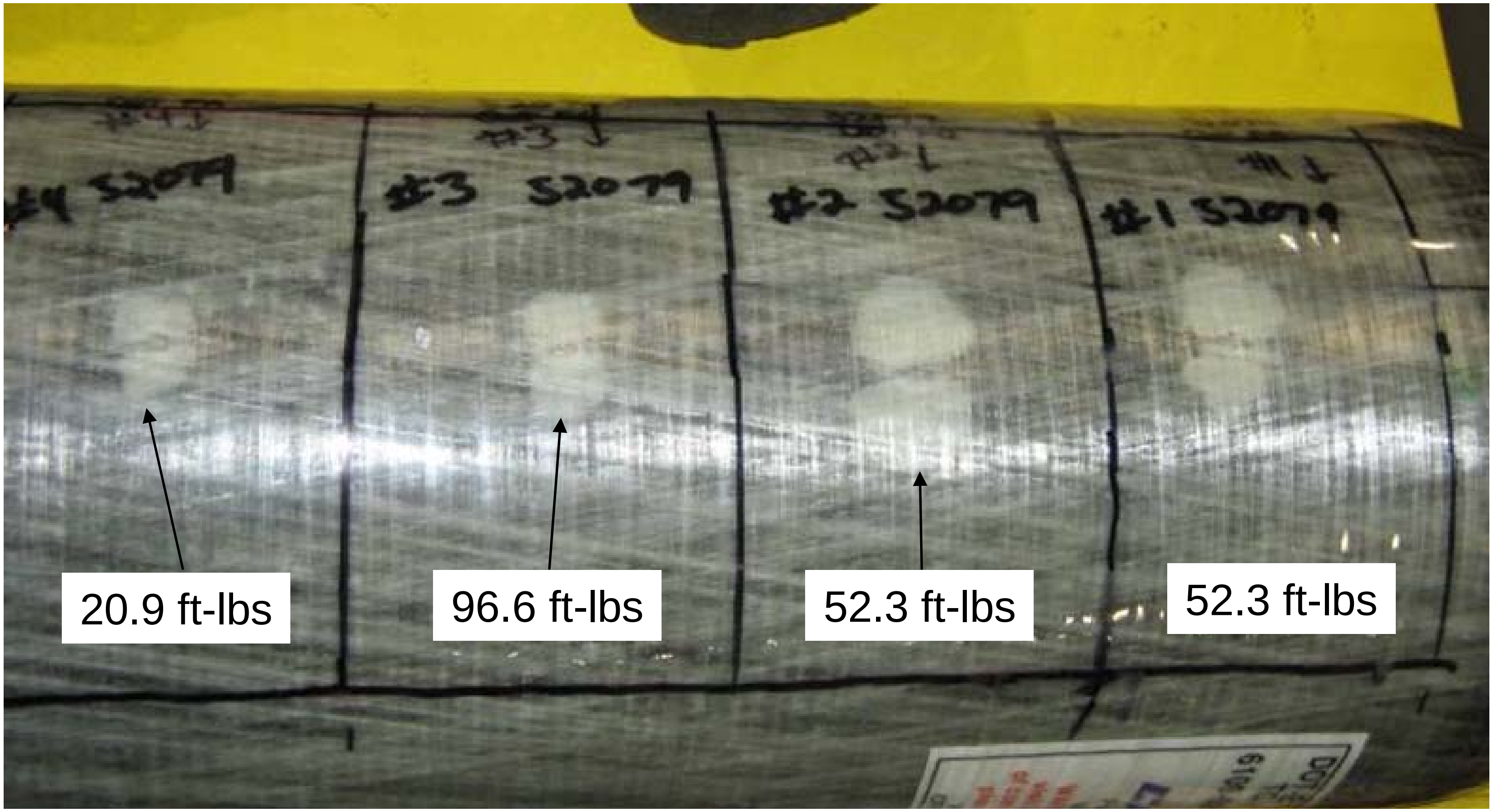
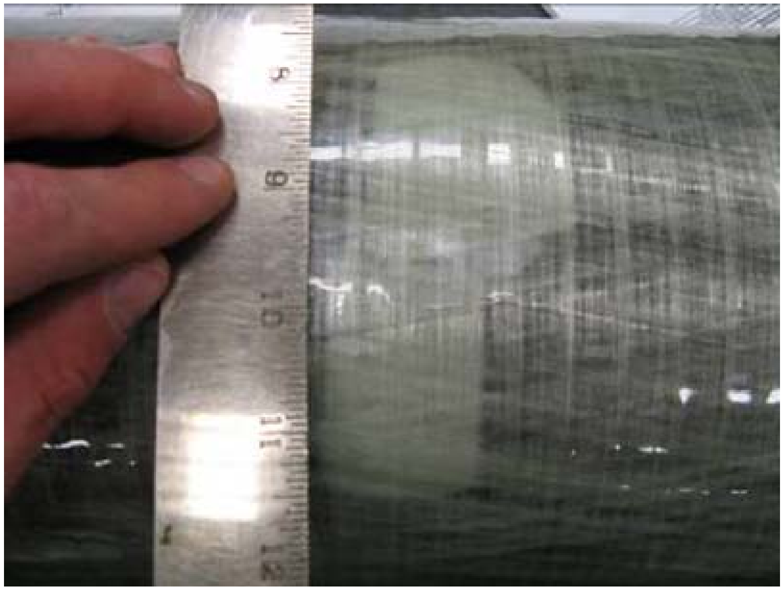


Figure 13. Photograph of cylinder 52079 opposite side



Visible glass layer delamination
was ~2 inches long axially and
~4 inches long circumferentially

Bottle surface was dented to
a depth of 0.12 inches

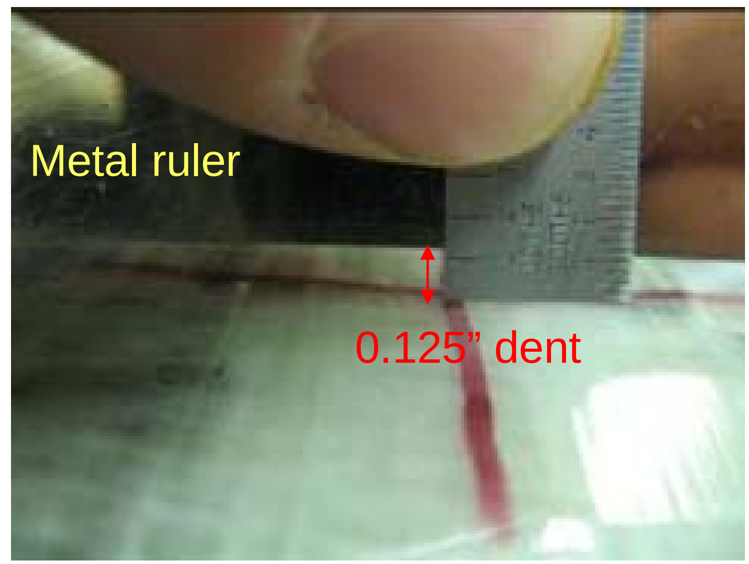


Figure 14. Photograph of cylinder 52093

Table II. Cylinder Damage Summary

Bottle #	Configuration	Location	Impact Energy	Al Dent Size	Displacement	Load	UT Circumference	Fiber Damage
52082	Half Bottle on wood	#1	98.5 ft-lbs	0.065"	0.35"	3846	2.51"	(3) hoop (2) helical layers. Most single tow
	Half Bottle on Steel	#2	98.1 ft-lbs	0.100"	0.15"	3803	3.88"	(4) hoop (1) helical layers. Most single tow
	Half Bottle on Steel	#3	51.6 ft-lbs	0.043"	0.09"	3039	3.50"	(2) hoop (1) helical layers. Single tow
	Half Bottle on Steel	#4	186 ft-lbs	0.150"	0.42"	4944	4.30"	Significant Fiber Fracture
52079	Full Bottle on Chocks	#1	38 ft-lbs	0.035"	0.39"	NA	0.86"	(2) hoop, less than tow width
	Full Bottle on Chocks	#2	52 ft-lbs	0.050"	NA	2965	1.18"	(3) hoop, about 1 tow wide
	Full Bottle on Chocks	#3	32 ft-lbs	0.022"	0.02"	2478	1.96"	(1) hoop, 1/2 tow wide
	Full Bottle on Chocks	#4	21 ft-lbs	0.009"	NA	2634	1.81"	(1) hoop, 1 tow wide
52079	Half Bottle on Steel	#1	15 ft-lbs	No Dent	0.25"	1789	0.55"	No Fiber Damage
	Half Bottle on Steel	#2	20 ft-lbs	0.011"	0.27"	2087	1.10"	2 Hoop layer Fractures, single tow
	Half Bottle on Steel	#3	20 ft-lbs	0.010"	0.29"	2087	0.94"	No Fiber Damage
	Half Bottle on Steel	#4	20 ft-lbs	No Dent	0.31"	2301	0.71"	No Fiber Damage
52089	Full Bottle on Chocks	Only One	24.8 ft-lbs	Not measured	0.16"	2566	1.26"	Unknown
52090	Full Bottle on Chocks	Only One	40.6 ft-lbs	Not measured	0.10"	2922	1.81"	Unknown
52093	Full Bottle on Chocks	Only One	245 ft-lbs	Not measured	0.65"	6680	NA	Unknown

Cylinders 52079 and 52082, both cut cylinders, were used to obtain fiber breakage data using the deply technique. Each cut cylinder had multiple impact sites in order to minimize the number of cylinders that were needed. Hoop cracks were measured by evaluating individual plies as shown in Figure 15. Hoop crack size data are listed in Table II.

Establish preliminary correlation between NDE data and the imposed damages.

As expected there is a general correlation between impact energy and the amount of damage in the composite over rap (as measured by NDE methods). For the impact energies used thus far in this study the correlation does not extend to burst strength reduction. This finding suggests that we have not yet identified the critical damage (lowers burst strength to unacceptable levels) threshold.

4.4 Impact Effects Modeling

Determine the extent of material property data needed (lamina/laminate) for Finite Element Modeling and perform any necessary testing in support of this need.

Damage modeling in composite laminates requires detailed information about the structure design in addition to accurate laminate material properties. It is necessary to determine direction specific material properties. Material testing is needed to determine these properties if they are not already known. These material properties are used to model the stiffness response as well as the strength capability of the composite. Table III shows a test matrix for generating lamina composite properties that can be used to create an orthotropic material definition for the composite in a finite element model. Figure 16 shows a typical composite laminate FE model that would attempt to model the effects of an impact event.

4.5 Structural Testing

Establish testing method/procedure.

Cylinder hydro testing was performed at ATK's Promontory high-pressure test facility using a standard test protocol. The protocol simply involves applying pressure at pre-defined ramp rates. Cost restraints limited the amount of instrumentation that was used on the test cylinders. Mid-cylinder strain as a function of pressure was measured with two long wire 'belly band' gages. Acoustic emission was measured with six B-1025 broadband AE sensors manufactured by Digital Wave Corporation. Sensors were placed every 120^{o} inboard of the cylinder tangent lines. Figure 17 shows a photograph of the test configuration.

Table III. Material Properties Needed for FE Analysis

Test Description	Objective	Test Item	Data Usage
Tensile Test	Obtain tensile properties: Stress, Strain, Modulus	Tow Test	Establish resin translation factor
Compression Test	Obtain compressive properties along fiber: Modulus, Strength, Strain, Poisson's Ratio	Flate Plate from hoop winding	Allowable
Mechanical Properties: Tension	Tension transverse to fiber: Modulus, Strength, Strain, Poisson's Ratio	4-inch Tube	Allowable
Mechanical Properties: In-plane Shear	In-plane shear: Modulus, Strength, Strain, Poisson's Ratio	4-inch Tube	Allowable
Mechanical Properties: Interlaminar Shear	Interlaminar Shear Strength	4-inch Tube	Allowable
Mode-I Fracture Toughness	Used for Damage/Crack Propagation	Neat Resin Sample	Allowable
Mode-II Fracture Toughness	Used for Damage/Crack Propagation	Neat Resin Sample	Allowable

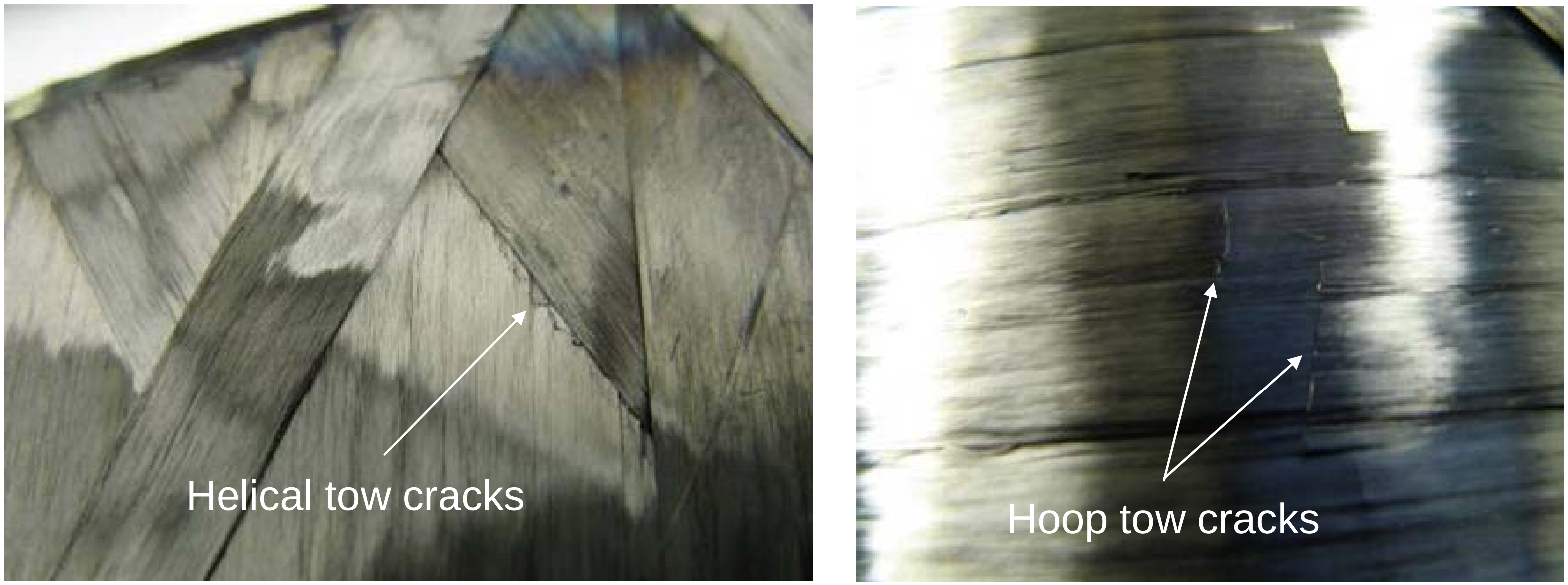


Figure 15. Photograph of typical deply result

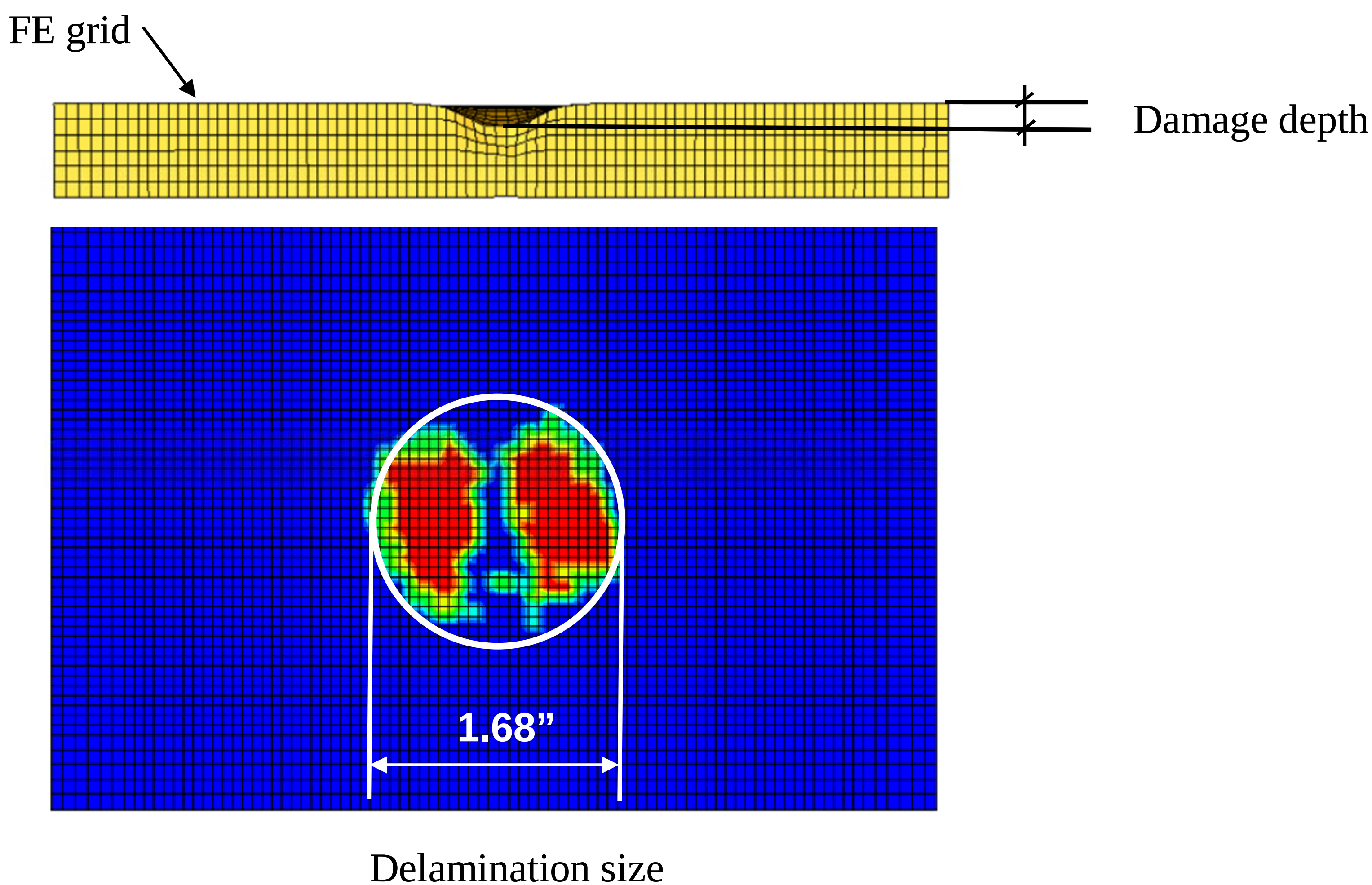


Figure 16. Example of FE model of impact damage

All sensors located ~1” inboard of tangent line at azimuths shown:

Sensor #1 - 0^{o} port end

Sensor #2 – 120^{o} port end

Sensor #3 – 240^{o} port end

Sensor #4 – 0^{o} dome end

Sensor #5 – 120^{o} dome end

Sensor #6 – 240^{o} dome end

Impact site located between sensors 1 and 4

Figure 17. Test cylinder hydro test configuration

Cylinder testing utilized a standard re-qualification pressure cycle. This cycle linearly increased the pressure at a rate of approximately 10 psi per second to proof pressure and then a pressure hold for 300 seconds. Pressure unloading was done at 130 psi per second. Burst tests are done using a straight ramp to failure using a 10 psi per second rate.

Determine baseline for undamaged cylinder strength.

Three cylinders were used to determine baseline undamaged strength. These cylinders failed at 19,344, 18,061, and 18,494 psi. These delivered strengths fall within a normal strength distribution we obtained from Carleton. Figure 18 shows our strength test results overlaid with the Carleton strength distribution data.

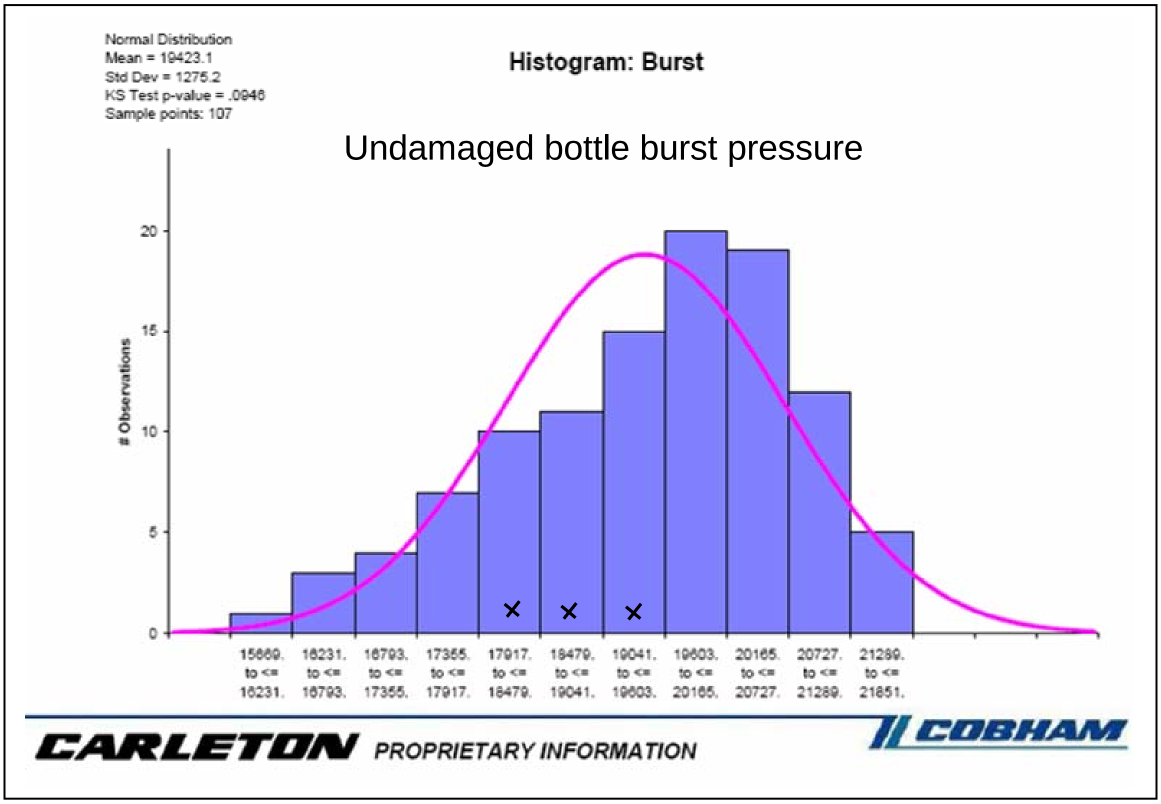


Figure 18. Undamaged cylinder strength distribution data

Characterize acoustic emission (AE) response of undamaged cylinders.

ATK has many years of experience with acoustic emission monitoring of pressure vessels undergoing hydro testing. We have established a baseline setup for instrument settings. These settings include amplifier and filter settings. These settings were used on the DOT cylinders with good results. Instrument performance is verified prior to test using standard pencil breaks on the surface of the cylinder.

Acoustic emission response of the undamaged composite over wrapped cylinders was typical of other composite pressure vessels that we test. This behavior is best visualized in the cumulative events versus time plot. The cumulative events versus time plot is shown in Figure 19 for cylinder 52075. Symbol type and color identifies the sensor location and symbol size identifies the event energy. Note that the events are uniformly distributed between all six sensors and that most event energies are low (small symbols). This behavior is typical of matrix cracking events. Event rates for all sensors are also similar. These data suggest the cylinder has uniform composite properties. When the pressure hold is reached event rates quickly drop to zero. This behavior is typical of well-made, undamaged pressure vessels. Events versus time plots are shown together for 52075 and 52078 cylinders in Figure 20. Note that the same behavior patterns are apparent in each of the cylinders. The slight difference in the total number of events is not unusual.

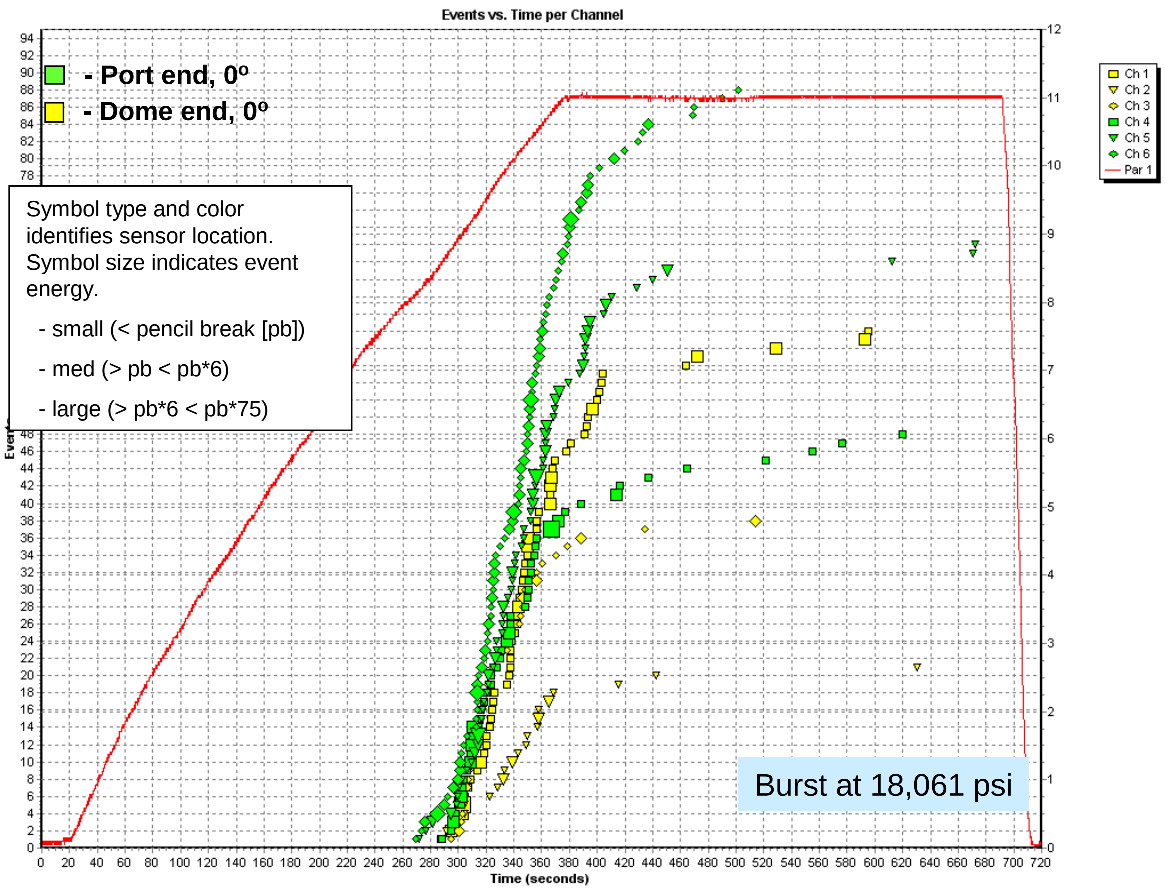
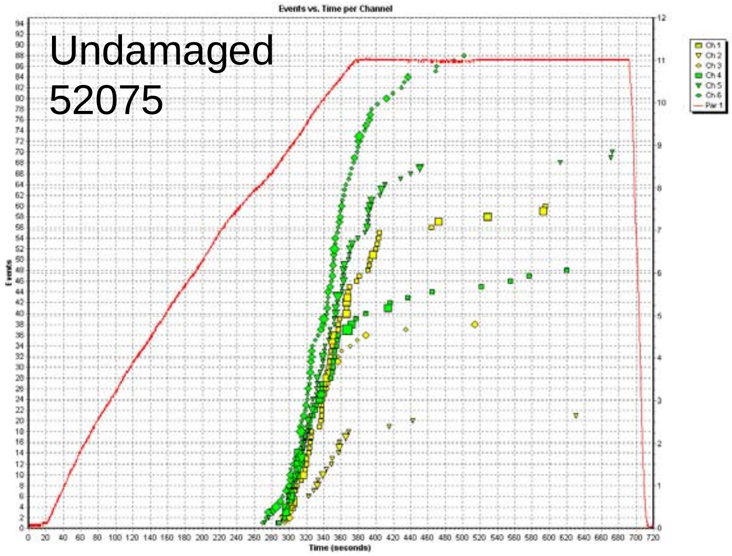


Figure 19. Typical undamaged cylinder AE results



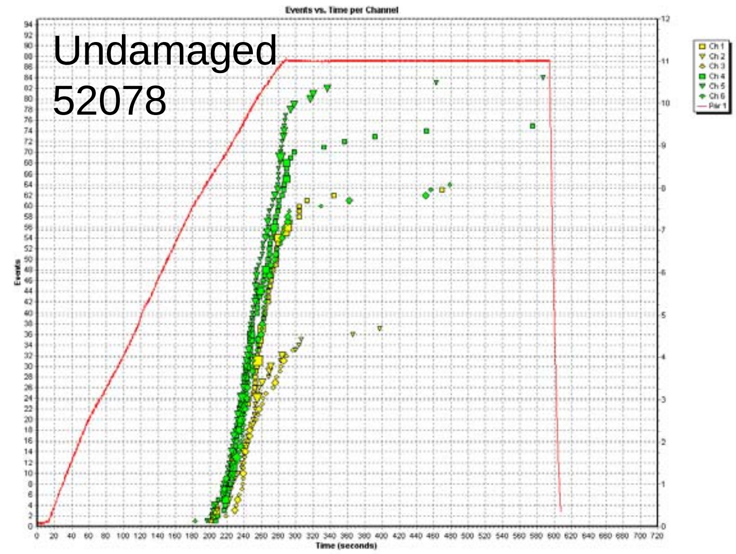


Figure 20. Events versus time plots for the two control undamaged cylinders

Characterize AE of damaged cylinders tested.

Three cylinders were tested after being damaged from an impact event. Impact energies were selected during the impact testing described above. Selected impact energies were 24.8, 40.6, and 245 ft-lbs. These impact energies cover the composite damage range from lightly damaged to extreme damage (relative to the standard drop test damage level). Test protocol was the same as the undamaged cylinder protocol. Figure 21 shows the cumulative events versus time plots for these three cylinders. Note that the general behavior was similar for all damaged bottles even though the damage level was different. Acoustic behavior for the damaged cylinders was also similar to the undamaged cylinders. This similarity can be seen in Figure 22. All cylinders exhibit uniform AE event rates during the ramp to proof pressure and a quick roll off of event rate during pressure hold. There was some variation in the total number of events however. Variation in total number of events is not unusual even for parts made from the same material lot.

Since the apparent damage level in the 245 ft-lb damaged cylinder was thought to be quite severe it was initially surprising that the AE signature did not discriminate this cylinder. However when one looks at the delivered strength of 16,681 psi and the stress strain behavior (Figure 23) it is clear that the level damage was not critical to the performance of this cylinder, at least in the re-qualification test scenario. The 16,681 delivered strength falls within the strength distribution data we received from Carleton (Figure 24) so the damage level was no more severe than standard manufacturing variation.

Testing to date has not considered damage effects when pressure cycling is considered. It is expected that cyclic loading will further degrade cylinder strength. We do not know by how much however.

Characterize baseline AE measurement for the damaged and undamaged cylinders.

The intent of this task was to establish a baseline measurement method for the AE technique. It is our current belief that the methods used in these tests are adequate for discriminating severely damaged cylinders. However this belief cannot be validated until further testing is done on cylinders with higher levels of damage since we have not determined the critical damage level yet. This will have to be left for a Phase II effect.

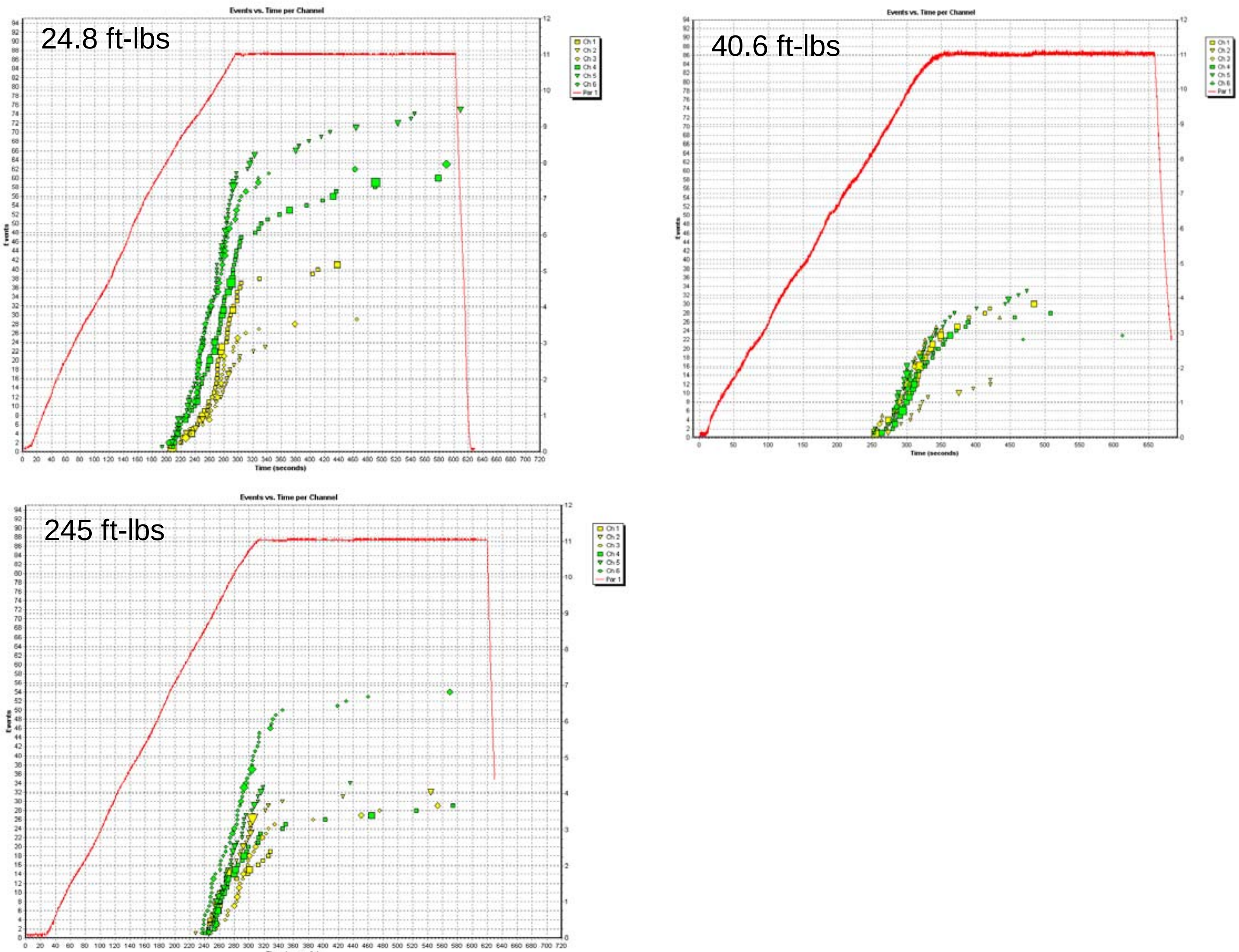


Figure 21. AE events versus time plots for the damaged cylinders

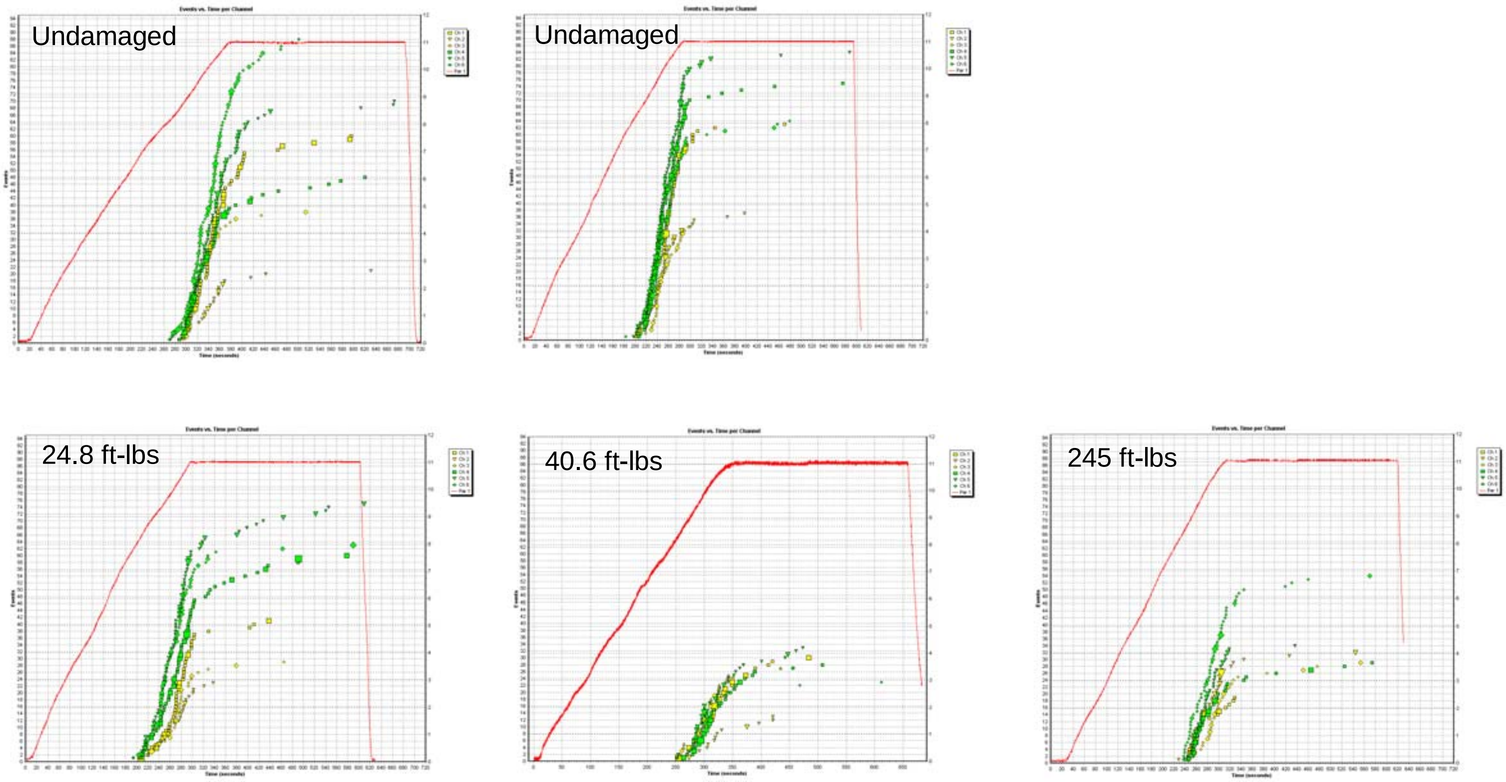


Figure 22. AE events versus time plots for all cylinders

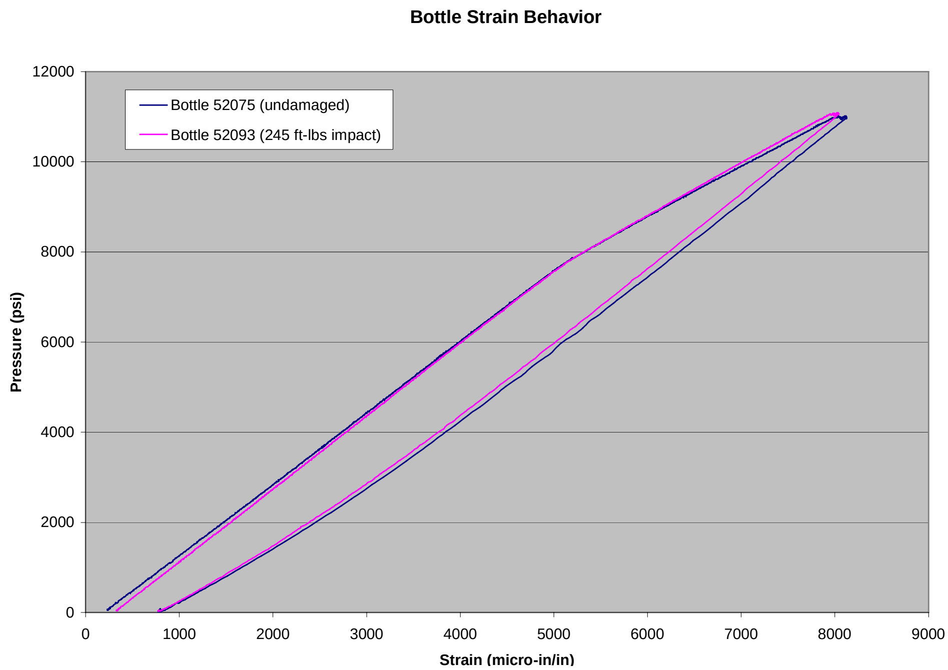


Figure 23. Stress-strain behavior of virgin and 245 ft lb cylinders

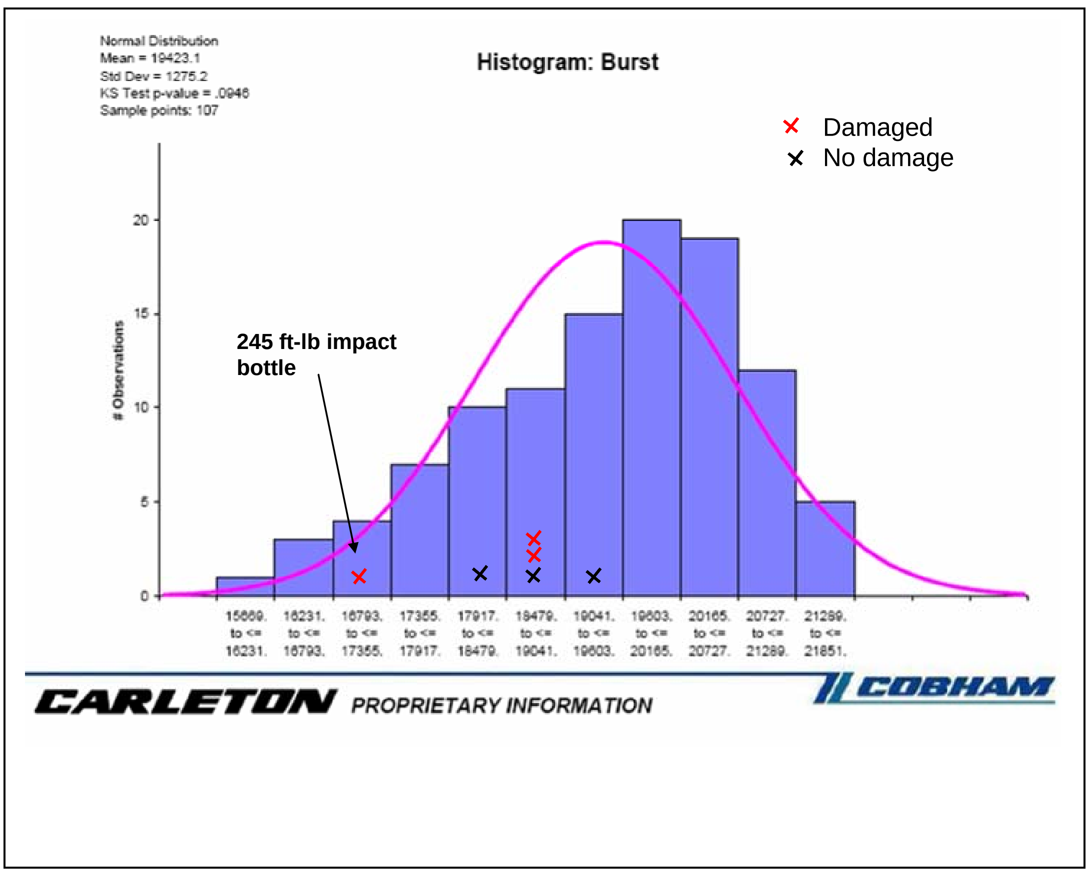


Figure 24. Burst results shown on Carleton strength distribution

5.0 SUMMARY

The Phase I effort was a qualified success. We were able to establish impact damage methods for the subject test cylinders, we developed a phased array method for sizing damage zone delaminations, and demonstrated the deply technique's ability to quantitatively measure fiber damage. We also induced several levels of damage in test cylinders so we know the basic fracture mechanisms that occur from impact events. We established procedures for applying acoustic emission instrumentation to cylinder re-qualification pressure cycles and measured the acoustic response of cylinders with varying levels of damage. What we didn't successfully do was identify the critical damage threshold for this cylinder type for a quasi-static load condition. As it turns out the defined scope of the Phase I effort was inadequate in this regard. Phase I also did not address any effects of cyclic loading.

It is worth mentioning that this particular cylinder design is very robust in terms of its ability to withstand a high energy impact event. We were quite surprised to see the high burst strength in the 245 ft-lb cylinder. Cylinders with this level of damage would most likely be rejected at re-qualification time based on visual acceptance criteria. We are note sure this would be true for cylinders with plastic liners.

6.0 RECOMMENDATIONS

The Phase I effort demonstrated our basic methodology for approaching the impact damage issue. We have confidence that this method will ultimately lead produce the information that DOT is seeking. Going forward it is obvious we need to direct our thinking to the effect of damage with a cyclic loading scenario. Our phase II proposal will address this issue. For other cylinder designs we would recommend pursuing a program that is similar to phase I.