Development and Manufacture of Cost-Effective Composite Drill Pipe

FINAL TECHNICAL REPORT

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ABSTRACT

Advanced Composite Products and Technology, Inc. (ACPT) has developed composite drill pipe (CDP) that matches the structural and strength properties of steel drill pipe, but weighs less than 50 percent of its steel counterpart. Funding for the multiyear research and development of CDP was provided by the U.S. Department of Energy Office of Fossil Energy through the Natural Gas and Oil Projects Management Division at the National Energy Technology Laboratory (NETL).

Composite materials made of carbon fibers and epoxy resin offer mechanical properties comparable to steel at less than half the weight. Composite drill pipe consists of a composite material tube with standard drill pipe steel box and pin connections. Unlike metal drill pipe, composite drill pipe can be easily designed, ordered, and produced to meet specific requirements for specific applications. Because it uses standard joint connectors, CDP can be used in lieu of any part of or for the entire steel drill pipe section.

For low curvature extended reach, deep directional drilling, or ultra deep onshore or offshore drilling, the increased strength to weight ratio of CDP will increase the limits in all three drilling applications. Deceased weight will reduce hauling costs and increase the amount of drill pipe allowed on offshore platforms. In extreme extended reach areas and high-angle directional drilling, drilling limits are associated with both high angle (fatigue) and frictional effects resulting from the combination of high angle curvature and/or total weight. The radius of curvature for a hole as small as 40 feet (12.2 meters) or a build rate of 140 degrees per 100 feet is within the fatigue limits of specially designed CDP.

Other properties that can be incorporated into the design and manufacture of composite drill pipe and make it attractive for specific applications are corrosion resistance, non-magnetic intervals, and abrasion resistance coatings. Since CDP has little or no electromagnetic force fields up to 74 kilohertz (KHz), a removable section of copper wire can be placed inside the composite pipe to short the tool joints electrically allowing electromagnetic signals inside the collar to induce and measure the same within the rock formation. By embedding a pair of wires in the composite section and using standard drill pipe box and pin ends equipped with a specially developed direct contact joint electrical interface, power can be supplied to measurement-while-drilling (MWD) and logging-while-drilling (LWD) bottom hole assemblies. Instantaneous high-speed data communications between near drill bit and the surface are obtainable utilizing this “smart” drilling technology.

The composite drill pipe developed by ACPT has been field tested successfully in several wells nationally and internationally. These tests were primarily for short radius and ultra short radius directional drilling. The CDP in most cases performed flawlessly with little or no appreciable wear. ACPT is currently marketing a complete line of composite drill collars, subs, isolators, casing, and drill pipe to meet the drilling industry’s needs and tailored to replace metal for specific application requirements.

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1. List of Acronyms and Abbreviations

AC	Alternating Current
ACPT	Advanced Composite Products and Technology, Inc.
AE	Axial Stiffness
AWG	American Wire Gauge
C	Centigrade
CDC	Composite Drill Pipe
cm	Centimeter
dB	Decibel
DDD	Deep Directional Drilling
DOE	Department of Energy
DV	Dump Valve
EI	Bending Stiffness
ER	Extended Reach
F	Fahrenheit
FSK	Frequency Shift Keying
ft-lb	Foot Pounds
GJ	Torsional Stiffness
gpm	Gallons per Minute
ID	Inside Diameter
IDR	Integrated Directional Resources
IF	Internal Flush (Thread)
in	Inch
K	x1000
KHz	Kilohertz
kPa	Kilopascals
K_{si}	Kilopounds per Square Inch
L	Length
lb(s)	Pound(s)
lb-in^2	Pounds per Square Inch
Lb-ft	Pounds per Foot
LWD	Logging-While-Drilling
m	Meter
M_{si}	Megapounds per Square Inch
MWD	Measurement-While-Drilling
N	Newton
NETL	National Energy Technology Laboratory
OD	Outside Diameter
P_c	Rated Compression Load
P_i	Rated Internal Pressure
P_t	Rated Tension Load
PDO	Petroleum Development of Oman
PEK	Polyether Ketone

psi	Pounds per Square Inch
psig	Pounds per Square Inch Gauge
PSK	Phase Shift Keying
PWM	Pulse Width Modulation
SAR	Slurry Abrasion Resistivity
SBS	Short Beam Shear
SDP	Steel Drill Pipe
SR/CDP	Short Radius / Composite Drill Pipe
T	Rated Torsion Load
TD	Total Depth
UD	Ultra Deep
USR/CDP	Ultra Short Radius / Composite Drill Pipe
VDC	Volts Direct Current
V p-p	Volts Peak to Peak

2. Executive Summary

Composite drill pipe could bring new life to thousands of idle wells drilled in the early 20th century. In many fields, unproduced oil-bearing formations lie 100 feet (30.5 meters) or less below the total depth (TD) of existing wells or remain bypassed behind casing because the reserves were not considered significant when the well was drilled. Using short radius drilling to drill horizontal laterals into these formations from existing wells could bring many of these older wells back into production without the environmental disturbance that drilling new wells from the surface could create.

In addition to its short radius drilling applications, CDP shows promise for enabling the economic development of oil and gas resources in other challenging locations. Because CDP combines lighter weight (less than half the weight of steel) with the performance properties of steel pipe, it is considered one of the technologies needed for resource development in extended reach (ER), ultra deep (UD), and deep directional drilling (DDD) applications.

Onshore, CDP will allow the existing fleet of drill rigs to drill at much greater depths. Significant potential exists to enable technologies requiring high-speed communications and data transfer ("smart" drilling technologies) through the composite drill pipe via embedded cables and/or fiber optic leads within the drill pipe body. The decreased loads required to be transported and supported by drilling platforms can provide substantial cost savings for deep offshore drilling and deep water drilling activities.

While the use of composites has increased significantly over recent years, their cost and performance have kept them from being more widely used. With the advance of carbon fiber technology, composite structures are beginning to demonstrate performance capabilities comparable to steel. With carbon fibers costing less and pipe designs becoming more sophisticated, the opportunity exists to develop drill pipe that can be cost competitive with steel. Due to these factors, the U.S. Department of Energy has provided funding through the National Energy Technology Laboratory (NETL) to accelerate development of this much-needed capability as part of an overall drilling technology portfolio to meet tomorrow's resource development challenges.

CDP consists of a composite material tube with steel box and pin connections. The tube is manufactured by winding graphite fibers and epoxy resin around a metal mandrel and the metal box and pin connections. Once the composite is cured, the metal mandrel is removed. The cured pipe section is machine finished and abrasion resistant coating applied.

During this multiyear DOE/NETL supported research and development program, specifications for both nominal 6-inch (15.2 cm) and 2-1/2 inch (6.35 cm) composite drill pipe were finalized; materials for the composite tubing, adhesives, and abrasion coats were selected based on laboratory testing; and a composite tube/metal tool joint interfacial connection successfully tested. Existing facilities were modified to allow for "pilot plant" production of 30-foot (9.14 m) sections of CDP.

Development of the 2-1/2 inch (6.35 cm) short radius CDP was completed and successfully field tested in "horizontal' lateral drilling operations. The 2-1/2 inch (6.35 cm) diameter was successfully used to drill a 1,000-foot horizontal lateral from an existing well at a depth of 1,200 feet and also to drill a 60-foot radius, 1,000-foot lateral through hard sandstone from a shallow, 1,385-foot well. On the basis of knowledge gained from some failures using the 2-1/2 inch CDP for ultra short radius (USR) drilling in Oman, another 2-1/2 inch CDP was developed that would reduce the 50 to 60 foot minimum short drilling radius to 30 feet (9.14 m) required for ultra short radius (USR) drilling. Initial bench-scale testing of the "smart" composite drill pipe critical link—the metal ends—for built-in data and energy transfer within the CDP walls has been demonstrated. The CDP is currently being marketed by ACPT with several joints having been sold.

3. Background

Deep, extended reach, and deep water drilling are limited to a certain extent by the weight of steel drill pipe. The lighter the pipe, the less torque and drag are created, and the greater the distance that can be drilled both vertically and horizontally. Also, the depth to which drilling can be carried out from offshore drilling vessels is limited by the weight carrying capacity of those vessels.

In materials science, a composite is defined as "a complex material, in which two or more distinct, structurally complementary materials combine to produce structural or functional properties not present in any individual component." Composite materials made of carbon fibers and epoxy resin offer mechanical properties comparable to steel at less than half the weight. Pipe made from such composite materials offers superior flexibility for drilling short radius well bores required for extended horizontal laterals at shallow depths. High speed data transfers could be facilitated via cables or fiber optic leads embedded within the body of the pipe during construction. Because carbon composites are becoming less expensive to manufacture, the opportunity exists to develop a composite drill pipe (CDP) with some or all of these features that is cost competitive with steel drill pipe. Additionally, sections of CDP can be optimized for specific applications since the composite properties are well established and are a function of the resin and fiber types used and fiber amount and orientation.

Composite drill pipe consists of a composite material tube with steel box and pin connections. The tube is manufactured by winding graphite fibers and an epoxy resin around a metal mandrel and the steel box and pin connections. The resultant pipe is cured and the mandrel removed. The cured pipe section is then machine finished and abrasion resistant coating is applied to protect the composite fibers. Standard centralizers are added in the field to further protect the composite section. While the coating can be repaired in the field, more extensive wear (should it occur) must be repaired in the factory.

A focus of the Department of Energy's National Energy Technology Laboratory (NETL) is to work with industry to reduce risk through cost sharing in the development of technologies NETL considers essential for future development of domestic resources. As an additional driver for this interest, demand is expected to increase significantly beyond the available supply of conventional and unconventional domestic resources by 2020, and fosters development of technologies that would enhance resource development and thus help mitigate such national energy security issues.

One key technology is composite structures, more specifically, composite drill pipe. Because composite drill pipe has the potential to be lighter (equal to or less than one-half the weight of steel) and maintain required performance properties, it is considered one of the technologies potentially essential for offshore and ultra-deepwater resource development. Onshore, it will allow the existing fleet of drill rigs to drill to much greater depth (Deep Trek). A third benefit is its significant potential to enable high speed communications (for smart drilling) up the drill pipe because of the ease of placing cables and/or fiber optics leads within the pipe body. The ability to enclose wire within the composite drill pipe walls will allow direct power supply from well head to drill bit front.

While the use of composites has increased dramatically in recent years, the cost and performance of these structures has kept them from being more widely used. With the advance of carbon fiber technology, composite structures are beginning to demonstrate performance capabilities comparable to steel. Now that carbon fibers are getting cheaper and pipe designs more sophisticated, the opportunity exists to develop pipe that can be cost competitive with steel. Hence DOE’s interest in attempting to accelerate development of this much-needed capability as part of its overall drilling technology portfolio to meet tomorrow’s resource development challenges.

A multiyear developmental program was sponsored by the U.S. Department of Energy, Office of Fossil Energy through the National Energy Technology Laboratory (NETL) to further rapid development of cost-effective composite drill pipe manufacturing capabilities within the United States. The primary project objective was to develop and demonstrate “cost-effective” composite drill pipe. The drill pipe was anticipated to weigh less than half of its steel counterpart, accommodate a much shorter directional drilling radius, and be capable of carrying real-time data signals and power transmissions within its walls.

4. Extended Reach/Deep Water Composite Drill Pipe

Initially, the impetus to develop “cost-effective” drill pipe was limited to its potential for weight savings—approximately half that of comparable steel pipe. Further examination of the literature and discussions with knowledgeable drilling experts defined additional potential applications.

4.1 Enabling Technologies

Problems associated with extended reach, ultra deep, and deep directional drilling are described by Smith, Chandler, and Boster (2001). They pointed out that current limits are controlled by the strength to weight ratio of steel drill pipe. Materials with higher specific strength ratios will increase these limits in all three drilling applications. The strength to weight ratio of nominal 6-inch composite drill pipe is 625,000 in 30-foot (9.14 m) sections and 1,011,000 in 45-foot (13.7 m) sections compared to 480,000 for 135 steel and 750,000 for titanium. This results in a 62.4% or 101% improvement over steel drill pipe and -9.3% (30-foot section) or 34.8% (45-foot section) improvement over titanium. Calculations for drill pipe in 10 pounds-per-gallon drill mud provide the following comparisons: the maximum depth allowable would be 32,000 feet (9,754 m) for 6 5/8 inch (15.6 cm) 27.70 Grade S steel drill pipe, 50,000 feet (15,240 m) for titanium, and 50,000 –70,000 feet (15,240–21,366 m) for composite drill pipe depending on the grade of carbon fiber used (Leslie, et.al, 2006).

While increased strength to weight ratio is always advantageous, each drilling application places somewhat different requirements on the drill pipe. In extended reach (where Reach/Total Vertical Depth is 0.75) the limits are associated with both high angle (fatigue) and frictional effects resulting from the combination of high angle curve and/or total weight. Composite drill pipe can be designed for flexibility such that the radius of curvature for a hole as small as 40 feet (12.2 m) [140 degrees per 100 feet] is within the fatigue limits (Hareland et.al, 1997). Eckhold, Bond, and Hasely (1991) presented a case wherein the possible horizontal reach is three times that of steel drill pipe for a medium radius horizontal well that was attributed to a lower frictional loading weight (light weight composite drill pipe).

Unlike any metal drill pipe, composite drill pipe can easily be designed, ordered, and produced to meet specific requirements for specific applications. Mechanical properties are well established and are strictly a function of the resins and fibers used and the orientation and amount of fiber in the composite drill pipe tube, allowing any section(s) of the pipe to be optimized for a given requirement. (More longitudinal fibers are used to increase tension and compression strength, hoop fibers to increase pressure capability, and fibers at a nominal 45 degrees to improve torque capacity.) Fibers with different properties are available and can be used to upgrade the properties of the pipe (at higher cost) or produce more economical composite drill pipe if high quality pipe is not needed.

4.2 Cost Issues

Cost issues must also be considered. Composite drill pipe (CDP) production costs are on the order of three to five times that of “standard” S-135 steel drill pipe. Several items need to be addressed in this regard. First, the CDP represents an enabling technology allowing deeper and longer reach drilling than is possible with metal drill pipe. In addition, the drilling limit is often not the drill pipe; rather it is the lifting or torque applying capability of the rig. Another rig limitation can be the deck loads on a floating offshore vessel. Lighter drill pipe can increase both.

Second, special (expensive) precautions must be taken when steel drill pipe (SDP) reaches its technical limits. That is, SDP has more stringent manufacturing requirements and requires more stringent and frequent field inspections. It is not as robust a design when near the technical limits. Thus, even where SDP may be used (near technical limit) CDP will lower the loads and operate at a smaller percentage of its limit. It is also noteworthy that for these applications the CDP will have much higher fatigue properties than its steel counterpart.

Third, CDP can easily be “tailored or customized” based on mechanical properties for application and/or location in the drill string. For example, in an extended reach well, steel drill pipe would likely be used in the larger vertical drill hole sections, while CDP would be used in the curve and high hole angle sections of the well. This allows optimization not possible when only SDP is used. Thus, even though CDP will always be more expensive than SDP on a joint per joint basis, the cost/performance of the total drill pipe string can be optimized.

Fourth, and very importantly, with the weight of the drill pipe at 40% to 50% that of steel (Figure 1), the loads to be transported and the weight supported by the drilling platform are significantly reduced and can provide very substantial cost savings.

Fifth, when the capability to reliably transfer real-time signal (and power) across the metal tool joints is reduced to practice, the cost of drilling can be drastically reduced. This reduction will be effective in all drilling operations, not just extended reach or deeper drilling.

Figure 1. A 30 foot section of composite drill pipe is being carried by a 9/10 year old sister/brother team to demonstrate the light weight of CDP.

4.3 6 Inch (15.2cm) CDP for Deep Water and Extended Reach Drilling

Initial work on this project concentrated on specifying the requirements for a “typical” drill pipe as a target for the CDP. These requirements have been continuously refined during this program and will continue to be upgraded as experience in the manufacture and use of CDP is obtained. Initially, industry partners supplied mechanical requirements identical to those of 5 7/8 inch (14.9 cm) high-strength steel drill pipe. These were reviewed and modified through open forum industry discussions. Revised mechanical requirements were then converted to conform to the mechanical/weight characteristics possible with low-cost graphite/epoxy materials. More recently, the required mechanical specifications have been exhaustively analyzed through joint efforts with our partner, Omsco. These results have been applied and are reflected in the nominal 6” (15.2 CM) CDP specifications shown in Table 1.

4.3.1 Program Development

The testing portion of this project includes initial material screening through final in-ground evaluation of market-ready CDP. The material screening and material properties verification portions are complete. Laboratory testing included verification of mechanical, thermal, and environmental properties of resins, fibers, and adhesives, and measurement of erosion and mechanical abrasion characteristics of interior and exterior coatings for CDP is complete. A program of extensive laboratory and field testing of full 30 foot (9.14m) sections of USR/CDP is in progress.

Table 1. Extended Reach Deep Water Product Data Sheet

	<u>Mechanical Specifications</u>	
Bending Stiffness	EI	180×10^6 lb-in^2
Torsional Stiffness	GJ	115×10^6 lb-in^2
Axial Stiffness	AE	33.4×10^6 lb
Rated Tension Load	P	450,000 lbs
Rated Torsion Load	T	25,000 ft-lb
Rated Compression Load	P_c	250,000 lbs
Rated Internal Pressure	P_i	9,500 psi
Max Service Temperature	F	350^{o}F
	<u>Design Specifications</u>	
Tube Inside Diameter	ID	5 in
Tube Outside Diameter	OD	6 in
Length (Pin-to-Box)	L	30 ft
Centralizers		Optional
Weight/30 ft	Lb	375 lbs
	<u>Connection Specifications</u>	
Pin/Box Diameter	OD	7 in
Bore	ID	4 ½ in
Thread	IF	NC 56

4.3.2 Materials Testing and Selection

Laboratory testing included verification of mechanical, thermal, and environmental properties of resins, fibers, and adhesives. Additionally, measurements of erosion and mechanical abrasion characteristics of the interior and exterior CDP coatings were performed.

Temperature capability and environmental resistance were evaluated through short beam shear (SBS) and in-plane shear tests. SBS testing provides an excellent screening tool for evaluating the mechanical relationship between the resin and the fiber in composite structures. Short beam shear tests were run on the selected materials after exposure to wet and dry temperature environments ranging from 200 to 400^o F (93 to 204^o C). Wet specimens were conditioned by both 24 and 100-hour water boil exposure. Test results are presented in Table 2. SBS tests were also performed after temperature and pressure exposure to water base and oil base drilling muds at a similar range of temperatures and simulated downhole pressures for 10 days.

Table 2: Short Beam Shear Tests per STM D2344

Temperature		Average Shear					
^{o}F	^{o}C	Dry		24 Hour Boil		100 Hour Boil	
		psi	kpa	psi	kpa	psi	kpa
200	93	5800	39,990	5280	36,404	4860	33,509
250	121	4690	32,336	4270	29,441	4180	28,820
300	149	4240	29,234	3820	26,338	3520	24,270
350	177	3920	27,027	3030	20,841	2730	18,823
400	204	2010	13,858	1520	10,048	1210	8,342

These tests proved that, as expected, the graphite fiber/epoxy matrix experienced a reduction in high-temperature shear strength after exposure to moisture. It is postulated that the strength degradation is caused by hydrolysis of the resin. However, this does not constitute a fatal flaw. Resin softening is a diffusion/controlled phenomenon and the very small (1/4 x 1/4 x 1 in [.635 x .635 x 2.54 cm]) SBS specimens present the absolute worst-case exposure conditions. Actual CDP will be a continuous tube with walls approximately 1/2 in thick and with environmental protection on both the inside and the outside surfaces. In addition, drill pipe does not experience long term continuous exposure at the most extreme environmental conditions. Therefore, a second set of 100 hour boiling water exposure tests were run with in-plane shear specimens and with 1/3 scale pipe. The results of these environmental exposure tests showed that the current composite matrix can be used in downhole conditions at up to 325^o F (163^o C). The approved materials as selected in this program are presented in Table 3.

Drilling at more elevated temperatures (i.e., ultra deep drilling) can be accommodated with higher temperature capable resin systems. Such systems are available, though their use at this time would increase the cost of producing CDP. Incorporation of a moderately higher temperature was consider, but was not done due to funding limitations.

Table 3: Summary of Materials Used in the Composite Drill Pipe

Fibers:

Carbon: Commercial Grade
Tow Size: 48K to 50K
Grade: 525 Ksi Fiber Strength, 33–34 Msi Fiber Modulus

Fiberglass: E-glass commercial grade
Tow Size: 450 Denier
Grade: 225 Ksi Fiber Strength, 10 Msi Fiber Modulus

Resin: 350^{o} F High Performance Resin

Adhesive: Low Density, High Strength, 350^{o} F Service Temperature Epoxy

As composites are much more susceptible to wear and abrasion than steel, it was recognized at the beginning of this program that CDP would have to be protected from mechanical wear. A dual approach has been developed and applied for protecting the exterior of CDP from abrasion: use of a highly wear resistant coating and centralizers.

ACPT screened more than 20 potential coating systems for external abrasion protection and evaluated five selected systems through Slurry Abrasion Resistivity (SAR) testing. SAR is a standard wear test used to measure wear resistance within slurry pumps and is accepted by the oil industry. Results showed that at least one coating system (numbered 2201 in Figure 2 and Table 4) compares favorably with 4130 steel. ACPT also evaluated “off-the-shelf” centralizers and determined that in addition to the abrasion resistant coating, field replaceable, high durometer electrometric centralizer units will need to be utilized with CDP. Steel centralizers are available and could be used in extreme abrasion conditions. Field use of SR/CDP proved the accuracy of these conclusions.

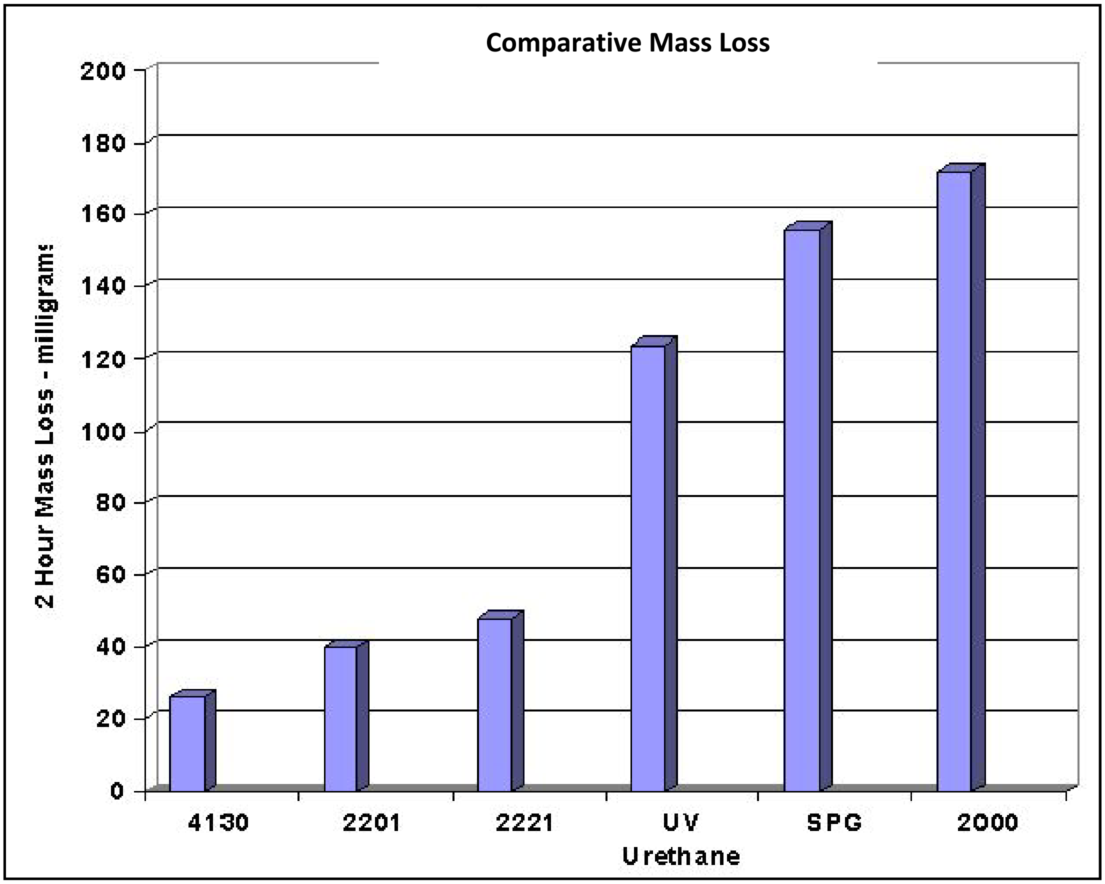

Figure 2. Results of abrasion testing of various coatings.

Table 4. Slurry Abrasion Response (SAR) Determination Results per ASTM G75-95

Material		Hour Mass Loss (milligrams)
4130 Steel	(Baseline)	25
2201 XXX		40
2221 XXX		45
UV Urethane		125
SPG XXX		158
2000 XXX		175

4.4 Pipe Testing

The major difficulty in producing a commercially useful composite drill has always been in developing the interface between the composite tube (pipe) and the steel joints. In order to reduce developmental costs, ACPT divided the CDP development into two distinct areas: subscale design and testing and full-scale design and testing. One-third size (diameter) was chosen for the small-scale effort and the full-scale work was broken into full diameter pipe in 10-foot sections and full diameter pipe at the maximum length of 31.5 feet (9.6m) (shoulder-to-shoulder) of metal joints.

Twenty-six (26) different 1/3-scale tension tests were completed. The results of these tests are summarized in Figure 3. Fifteen different combinations of composite/metal joint interface and composite wall configurations were evaluated. After testing showed that a successful composite/ metal interface design had been achieved, full size, 10-foot (3.05m) sections of CDP were fabricated and tested, as shown in Figures 4 and 5.

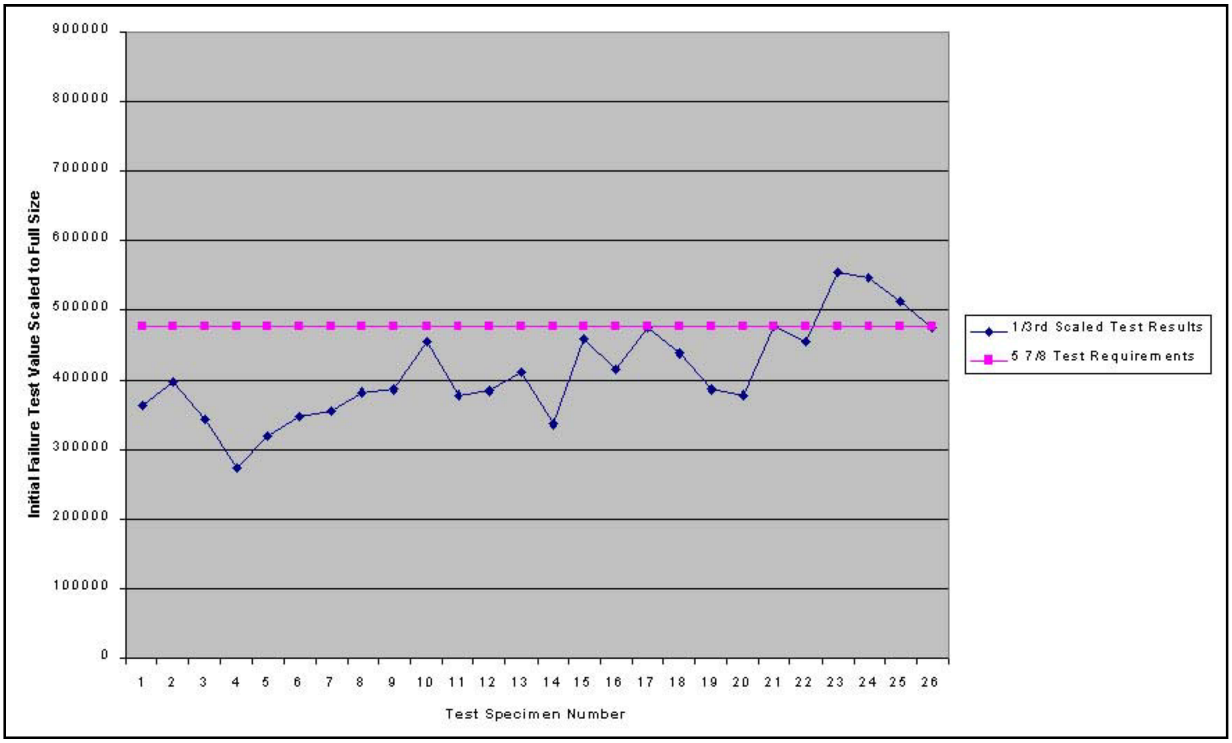

Figure 3. Tensile tests on 1/3-scale extended reach/deep drilling composite drill pipe

Figure 4. Ten-foot full diameter torsion test apparatus

Figure 5. Ten-foot full diameter tension test apparatus

As testing transitioned to the full size CDP specimens, the required tensile specification was raised from 478,000 (2,128,500 N) ultimate to 562,000 lb (2,502,000 N) ultimate. Thirteen full-scale tests, also incorporating design changes, were run. The results of these tests and the successful achievement of the 562,000 lb. (2,502,000 N) specification requirement are shown in Figure 6. The current ACPT control drawing for nominal 6 inch (15.2 cm) and 2.5 inch (6.4 cm) CDP are shown in Figures 7 and 8, respectively.

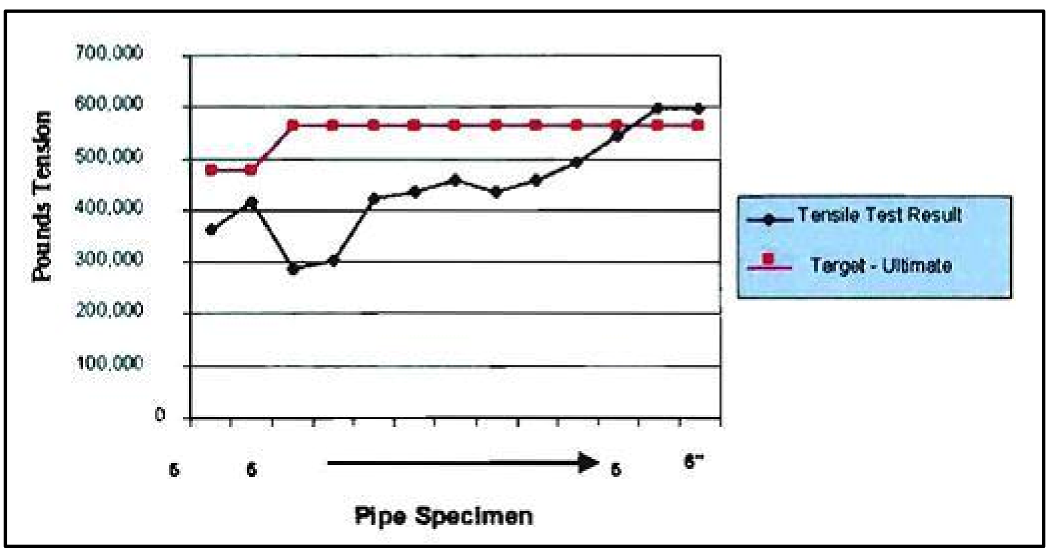

Figure 6. Full scale tensile tests on extended reach/deep well composite drill pipe

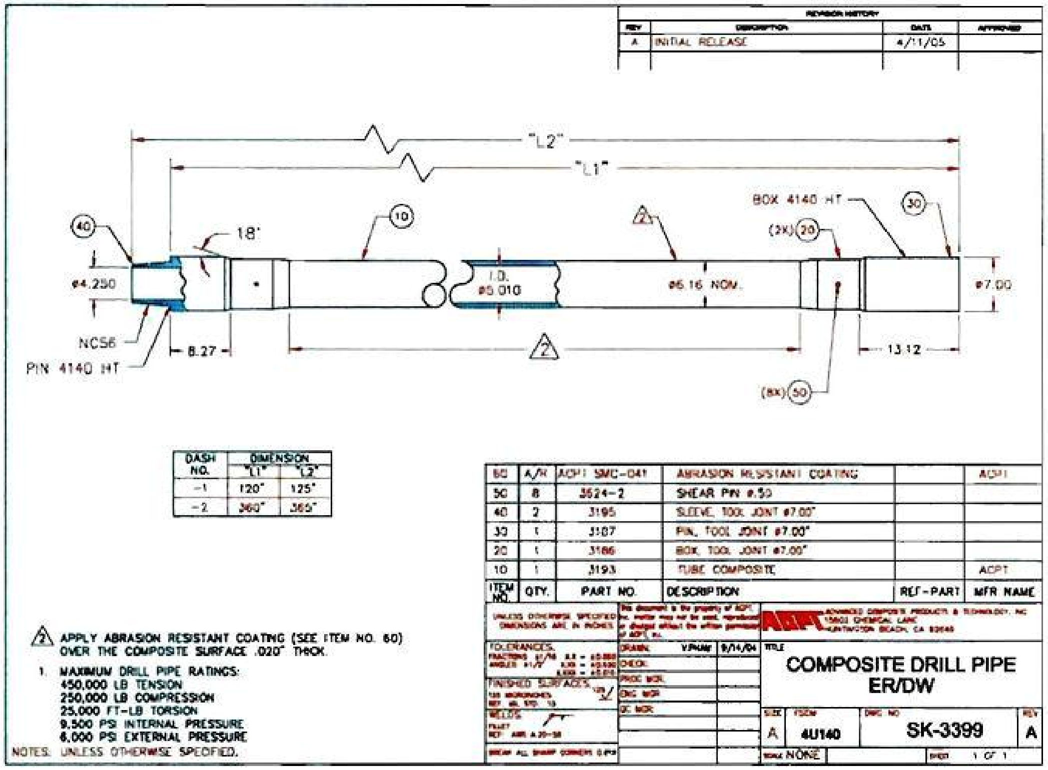

Figure 7. Source control drawing for 6-inch composite drill pipe.

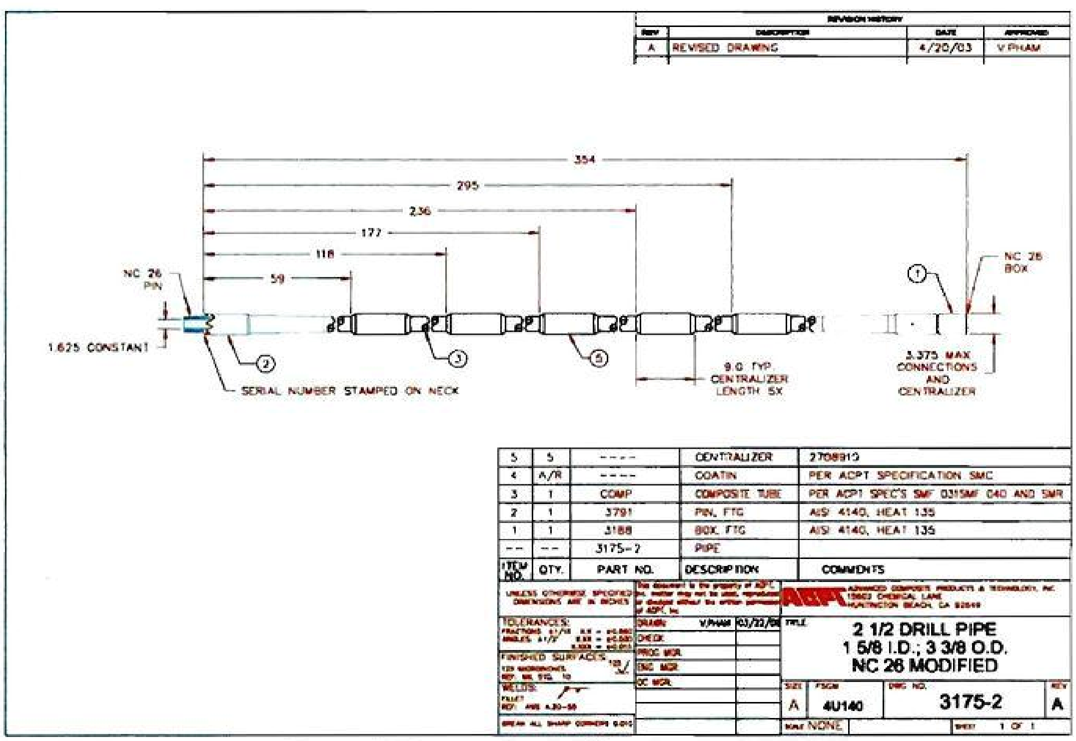

Figure 8. Source control drawing for 2.5-inch composite drill pipe

5. Short Radius Composite Drill Pipe (SR/CDP)

With much of the "easy-to-produce" oil and gas recovered, many companies are looking for lower cost methods to recover oil and gas that was bypassed when many fields were first developed. Short radius horizontal drilling is one technology that is being used to recover oil and gas from bypassed zones, many of which are shallow and of low productivity. However, one of the challenges facing the short radius drilling industry is the need for reliable drill pipe that can withstand the stress of drilling through short radius-of-curvature bends for extended periods of time.

In this ACPT/DOE CDP development program, in order to most efficiently use available funding, the initial metal joint/composite interface development was done with 1/3 scale CDP sections (1.417 inch [3.6 cm] ID with 12 inches [30.5 cm] of composite tubing between the metal end fittings). The smaller CDP with minor, easily achieved modifications was established, designs were modified, and 2 1/2" (6.35 cm) SR-CDP was built successfully.

5.1 Advantage of SR/CDP

Short radius drilling is being used to re-enter older, vertical wells and drill horizontal laterals into oil- and gas-bearing formations previously deemed uneconomic. These horizontal wells can encounter several hundred or perhaps even several thousand feet of reservoir rock, allowing them to drain substantially more oil or gas. But the sharp radius of curvature of a typical short radius reentry well, from 20 to 80 feet (6 to 24m), can create stress and fatigue damage that significantly decreases drill-string life and reliability.

Flexible composite drill pipe (CDP) overcomes this problem (Figure 9). Although more expensive than traditional steel pipe, it can remain bent for extended periods of time without suffering fatigue damage. Fewer pipe failures occur, fewer pipes are needed, and the pipe can be re-used in multiple wells leading to a significant reduction in drilling costs.

Figure 9. Short radius CDP is flexible enough to resist bending fatigue, but strong enough to carry 25,000 pounds of tension and 2,000 lb-ft of torque.

CDP could bring new life to thousands of idle wells drilled in the early 20th century. In many fields, oil-bearing formations previously considered uneconomic lie 100 feet (30.5 m) or less below well TDs or were bypassed because the reserves were not considered significant when the well was drilled. Using short radius drilling to drill a horizontal well into these formations may bring many of these older wells back into production without the expense and environmental disturbance that drilling new surface wells would create.

5.2 Experimental Field Evaluation of SR/CDP

Field tests of the short radius composite drill pipe (SR/CDP) have been completed. Initially, the CDP was employed in a short radius drilling application where the well was being drilled from vertical to horizontal within a 50 to 70-foot (15.2 to 21.3 m) radius. Also, only five to nine joints of composite pipe were used in each test and the pipe was always positioned in the drill string to be in the turn section of the well. The first test was performed by Grand Resources in Tulsa, Oklahoma, as they used the CDP to re-enter an older vertical oil well which had stopped producing in 1923. Just below 1200 feet (366 m), drillers kicked off a new borehole that curved in a 70-foot (21.3 m) radius until it became horizontal and then continued another 1000 feet (305 m) horizontally. The pipe performed flawlessly during this test (Figure 10).

Figure 10. Condition of joint end after use—a little rust on the steel end, but the composite has only a few scratches.

Grand Resources then used the pipe in a second well in which the pipe became stuck in the hole. During the effort to free the pipe, two joints failed; one joint broke in the middle and another broke at the metal connection/composite interface. Evaluation of the metal/composite interface break led to the interface being redesigned to create a much stronger juncture. A review of the drilling records determined that the CDP was not the reason that the pipe became stuck and that the mid-joint failure was a result of the extreme twisting and pulling forces applied during the effort to release the pipe.

A third field test was performed by JB Drilling in LeFlore County, Oklahoma (Figure 11). The SR/CDP was used in a new gas well to drill a 60-foot (18.3 m) radius turn for a horizontal lateral at a depth of 1385 feet (432m). A major difference in this test versus the Grand Resources tests was that an air-hammer drilling tool was used in this well. The air-hammer subjected the pipe to severe pounding stress, testing its fatigue life and mechanical strength. Also, the formation being drilled was very hard and abrasive providing an excellent test of the protective coatings used on the pipe. In this test the CDP was run for a total of more than 160,000 cycles at an average 70 RPM, 300 psi (2068 Kps) air pressure, and 1,000 lb-ft (1,335N) torque. The pipe was subjected to momentary pulls of 12,000 pounds (16,000 N), 10,000 pounds (13,350 N) of compression, and 1,500 lb-ft (2000 N) of torque. Despite this rigorous testing, the pipe performed flawlessly and after a week of drilling showed little to no signs of wear (Figure 12).

Figure 11. Short radius composite drill pipe delivered to J.B Drilling

Figure 12. After 160,000 air hammer cycles, the composite drill pipe exhibits little to no signs of wear.

Following successful completion of the preliminary field tests, the SR-CDP was offered on a limited (continuing field evaluation) basis to drilling companies. The first order under this testing plan was placed in January 2004 by Integrated Directional Resources (IDR) of Lafayette, Louisiana to air-drill Gulf Coast horizontal wells. The pipe was reported to be performing as expected. On location at one well in late July 2004, IDR reported problems with steel pipe failing while drilling the lateral section. IDR began using the composite pipe for all fishing operations, consistently pulling 20,000 to 25,000 pounds (89,000 to 111,000 N). Subsequent reviews of this work support the conclusion that the SR/CDP can be successfully used to re-open wells where the transition from "original well to horizontal" was equal to or greater than 150 feet (15 meters).

A fourth major proof test of the SR/CDP has been run in Oman where the desired minimum radius of curvature (ROC) was 30 feet (9.14 meters). Calculations on the CR/CDP indicated that it could be bent to 30 to 45 feet (9 to 14 meters) under no load conditions. This in-ground testing provided extremely valuable design/manufacturing information.

1. An improvement was needed in the "centralizer" (wear knot) bonding procedure.
2. The SR/CDP would fail prematurely when rotated at 23 to 33 ft (7 to 10 m) ROCs.
3. The SR/CDP must be completely redesigned to be useful in drilling down to a 30 ft (9 m) ROC.

5.3 Ultra Short Radius/ Composite Drill Pipe (USR/CDP)

The process for bonding the centralizers was revised and has been proven successful in field trials. A design specifically tailored to meet the 46 ft (14 m) operational ROC was completed and 30 ft. (9.14 m) trial sections manufactured. The USR/CDP specifications are compared to those of SR/CDP in Table 5. The redesign effort addressed manufacturing process improvements, improved the metal/composite interface, and resulted in some materials improvements as well as changes necessary to meet the reduced ROC (Table 6).

Table 5. Production SR/CDP and USR/CDP

Characteristic	ACPT SR-CDP	ACPT USR-CDP
Bending Modulus – msi (10^6 psi)	4.9	2.4
Shear Modulus – msi (10^6 psi)	3.1	2.5
Tensile Ultimate – lbs	75,000	65,000
Tensile Operating – lbs	25,000	25,000
Compression Ultimate – lbs	100,000	65,000
Compression Operating – lbs	50,000	25,000
Torque Ultimate – lb-ft	6,000	6,000
Torque Operating – lb-ft	2,000	3,000
Internal Pressure Ultimate – psi	2,000	3,000
Internal Pressure Operating – psi	1,000	1,500
Collapse Ultimate – psi	2,000	3,000
Collapse Operating – psi	1,000	1,000
Temperature – ^{o}F	325	325

Table 6. Short Radius Composite Drill Pipe Product Data Sheet

Mechanical Specifications

Bending Stiffness	EI	7.22×10^6 lb-in^2
Torsional Stiffness	GJ	11.30×10^6 lb-in^2
Axial Stiffness	AE	14.30×10^6 lb
Rated Tension Load	P	25,000 lbs
Rated Torsion Load	T	2,000 ft-lb
Rated Compression Load	P_c	50,000 lbs
Rated Internal Pressure	P_i	1,000 psi
Max Service Temperature	F	325^{o}F

Design Specifications

Tube Inside Diameter	ID	1 5/8 in
Tube Outside Diameter	OD	2 1/2 in
Length (Pin-to-Box)		30 ft
Centralizers		5 equally spaced
Weight/30 ft		92 lbs

Connection Specifications

Pin/Box Diameter	OD	3 3/8 in
Bore	ID	1 5/8 in
Thread	IF	NC26 or customer spec

Materials of Construction

Pipe body	E-glass/Graphite/Epoxy
Std Tool Joints	4140HT steel
*Non-magnetic Tool Joints	Stainless steel or customer spec
Wear Knots	Nitrile

*Non-magnetic tool joints may affect pipe ratings. Contact ACPT for further information.

6. Development of "Smart" Composite Drill Pipe

Discussions with industry personnel indicated a need to provide logging-while-drilling (LWD) and/or measurement-while-drilling (MWD) capabilities using the composite drill pipe. A significant feature of CDP is that it can carry power and/or real time communications through lines embedded in the composite walls.

6.1 Transfer of Real-Time Signals or Power through CDP

The problem to be solved was to reliably transmit signal and/or power through the metal joints connecting individual CDP sections. Several approaches to solving this problem have been examined.

6.1.1 Acoustic Transmission

Acoustic transmission is the ability to transmit data through the pipe joints utilizing sound waves. This concept was explored under a different DOE project.

6.1.2 Inductive Transmission

This approach shows positive potential. Sandia National Laboratory has investigated inductive transmission using wire coils to transmit signals across the joint unions. Inductive coupling has been considered and will be further investigated if the conceptual demonstrations show sufficient merit.

In anticipation of the development of a successful method for transmitting signals across metallic joints, Sandia National Laboratory has evaluated signal loss/transmission characteristics in CDP with wires incorporated into the walls of the pipe. The results proved conclusively that signal transmission can be accomplished. The concept has also been further explored by another contractor.

6.1.3 Direct Connection

Although this has been tried unsuccessfully numerous times in the past, a new approach to this technology has been successfully demonstrated in this program. Initially, 22 AWG paired conductors were selected for inclusion in the composite drill pipe. The process included embedding a nylon string on the outside of the carbon fiber structure to form a recessed passageway for the wire. The pipe was wrapped with release tape and cured. After cure, the release tape was removed along with the nylon string. The pipe was then machined to accept the tool joints. The tool joints are machined to accept the face rings and components to form the direct electrical connection. The pipe is bonded to the tool joints, welded, and pinned. The wire is then applied to the pipe in the wire way and connected to the face rings. Fiberglass is wound over the outside to complete the process.

6.2 Bayonet Connections

The design phase of the direct electrical connection program was subcontracted to Maurer-Noble Downhole Technology, Ltd. The approach selected for producing a direct electrical connection for rotary shouldered tool joints is shown in Figures 13–16. A circular groove is machined into the shoulder of the Pin connection. A highly conductive contact ring backed by an insulating member made of polyether ketone (PEK) is installed into this groove. The external surface of the contact ring is coated with a flexible, electrically insulating polymer. The electrical path is completed by attaching an insulated copper conductor to the back of the circular contact ring, which is embedded into the body of the composite drill pipe.

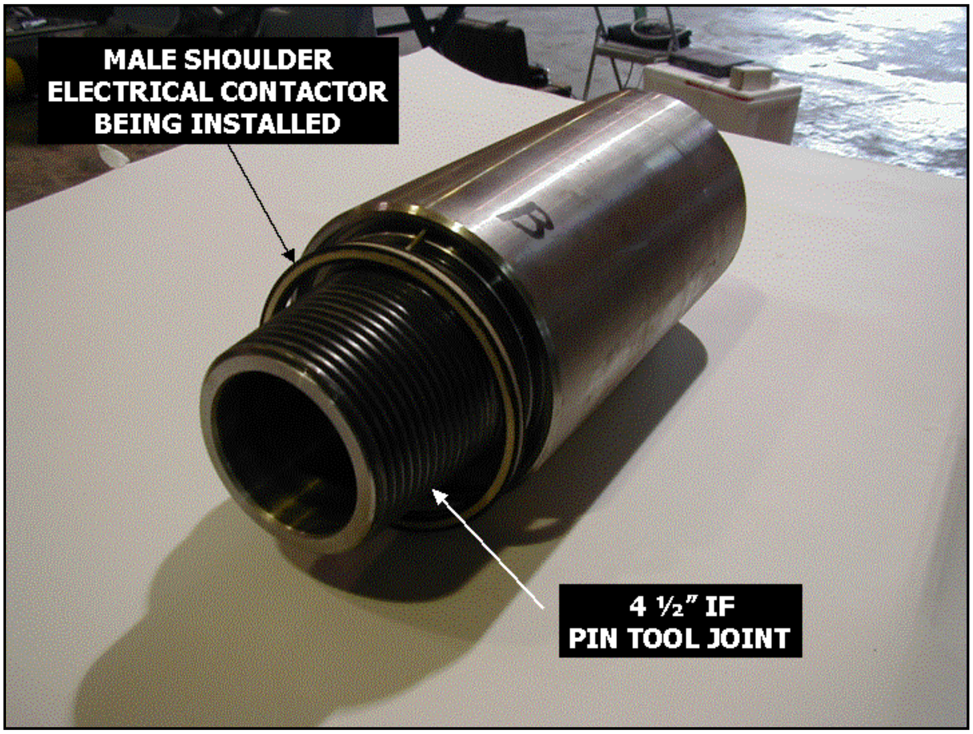

Figure 13. The 4-1/2 inch IF Pin connection components.

Figure 14. The 4-1/2 inch IF Pin connection fully assembled.

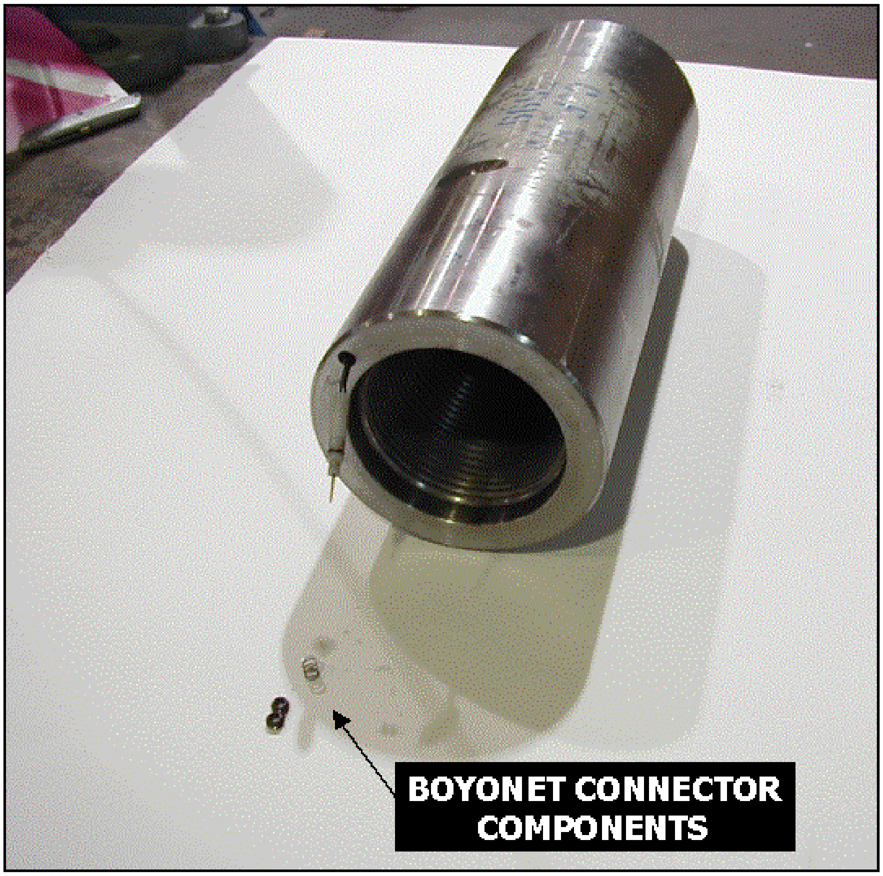

Figure 15. The 4-1/2 inch IF Box connection components.

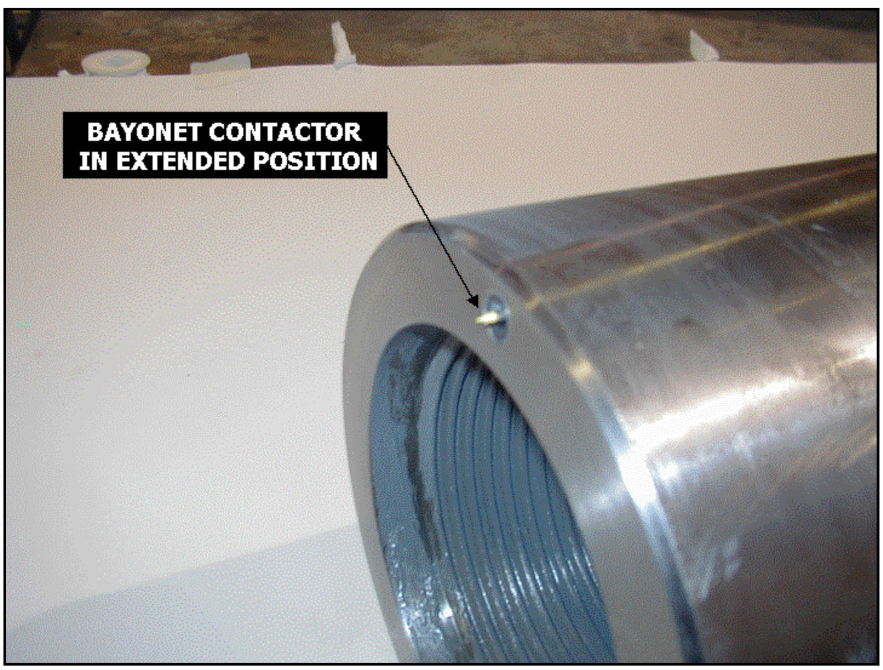

Figure 16. The 4-1/2 inch IF Box connection – bayonet extended.

The box connection of the tool joint had a drill hole that housed a circular cartridge held in place by a threaded hollow socket head cap screw. The cartridge consists of a metallic bayonet held inside a PEK insulator having the thermal and mechanical stability to withstand the rigors of the downhole drilling environment. A spring placed between the bayonet contactor and the tool joint shoulder keeps the bayonet below the surface of the tool joint shoulder during rig floor torque make-and-break operations. The spring rate will be chosen to set the minimum drill pipe pressure before the bayonet extends outward, pierces the insulating elastomer coating on the circular contact ring, and completes the electrical connection. Inspection of this design shows that it is not dependent on a specific angular alignment between the pin and box connections, has no active electronic elements, and should be relatively inexpensive to install and service once perfected.

The greatest value of composite drill pipe embedded with an electrical wire lies in matching the voltage ratings for typical logging cables. This will allow the CDP to be powered from standard wireline electrical power sources and operate the full range of LWD/MWD hardware. A maximum continuous DC voltage rating from 1200 volts can be realized with 18 AWG conductor, while 1500 volts is obtainable from 15 AWG. Recommendations called for ACPT to embed either a twisted pair or coaxial cable having AWG sizing from 16 to 10 with preference to use the largest wire size in this range that does not significantly detract from the composite pipe strength or present substantial fabrication issues.

For AC communications based on common encoding schemes such as frequency shift keying (FSK), phase shift keying (PSK), or pulse width modulation (PWM), the controlling element for communication is the signal attenuation versus frequency curve. Figure 5 is a typical attenuation curve for a mono-conductor logging cable, which also uses 15 AWG for its copper conductor measured for 25,000 ft. of wireline. Attenuation levels vary in proportion to depth.

The majority of MWD/LWD applications can be satisfied at DC power levels below 200 watts. Some typical power draws of MWD/LWD equipment are (1) positive mud pulsers (18–30 watts), (2) Directional/Gamma Ray sensors (14–18 watts), (3) Dual Frequency Resistivity (24–30 watts), and (4) Rotary Steerable (24–75 watts).

6.2.1 Initial Testing

Initial testing of the bayonet and circular ring direct electrical connection conducted using the pipe break out machine identified several areas in need of improvement. These improvements were made in May and June 2005 and the modified design was subsequently re-tested in a flow loop using three segments of composite drill pipe. The specific improvements made to the design were as follows:

- Changed spring spacer retainer from a cross pin dowel to a press fit in order to eliminate a potential fluid leak path
- Added an anchor pattern to the ring contactor groove on the pin connection to achieve better adhesion of the elastomer used to electrically insulate the contact ring from the drilling fluid
- Added a spacer to the bayonet shoulder, increased shoulder thickness, and relocated the o-ring gland to prevent bayonet damage at full stroke

In addition, flow and exit subs were designed and manufactured to support flow testing of the smart composite drill pipe segments.

6.2.2 Flow Loop Testing

Three segments of composite drill pipe were connected and plumbed into Maurer Technology's instrumented flow loop as shown in Figures 17–21. The power/data signal side wire and the ground return line from one end of the piping were connected to a DC power supply while the other lead ends were connected to an electrical load. The electrical load consisted of a small light bulb, which provided a clear indication as to whether the electrical circuit has been made when a certain pressure inside the drill pipe was achieved and electrical continuity was lost. The leads, in addition to being connected to the light bulb and multi-meter, were also periodically connected to an oscilloscope, which showed the power to be clean and free of the jitter that would be present if the bayonet and the contact ring were disengaged.

Figure 17. Composite pipe segment

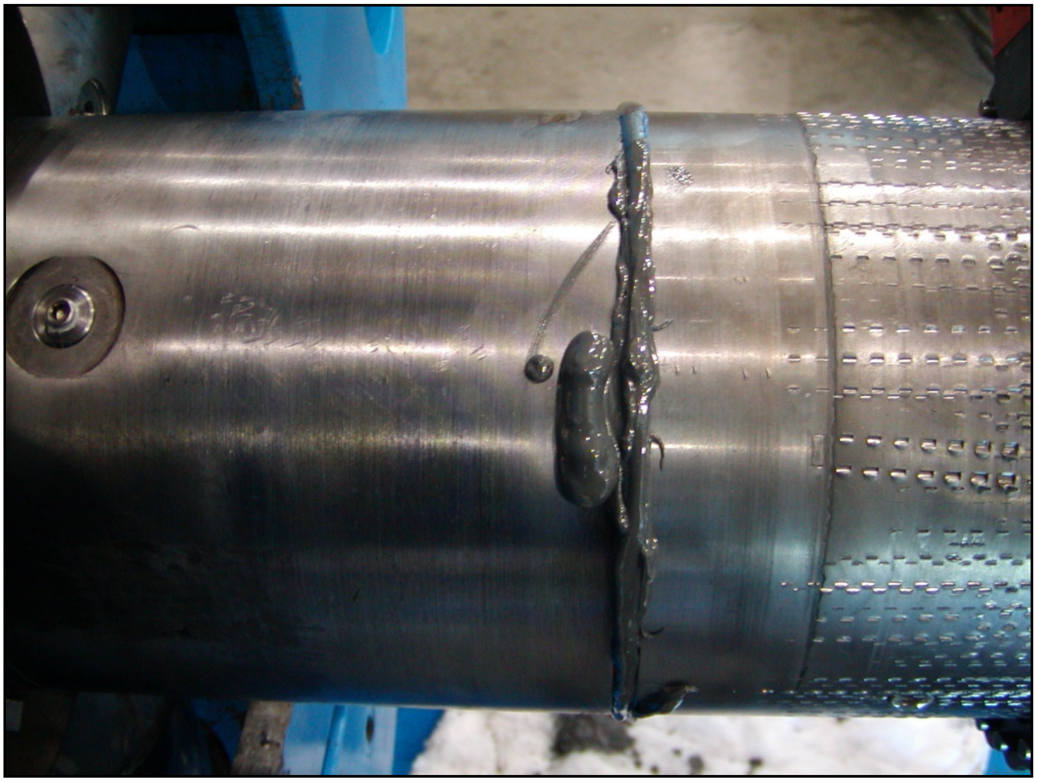

Figure 18. Torqued composite drill pipe tool joints

Figure 19. Composite drill pipes placed into flow loop

Figure 20. Flow control console, flow meter, and pressure readout

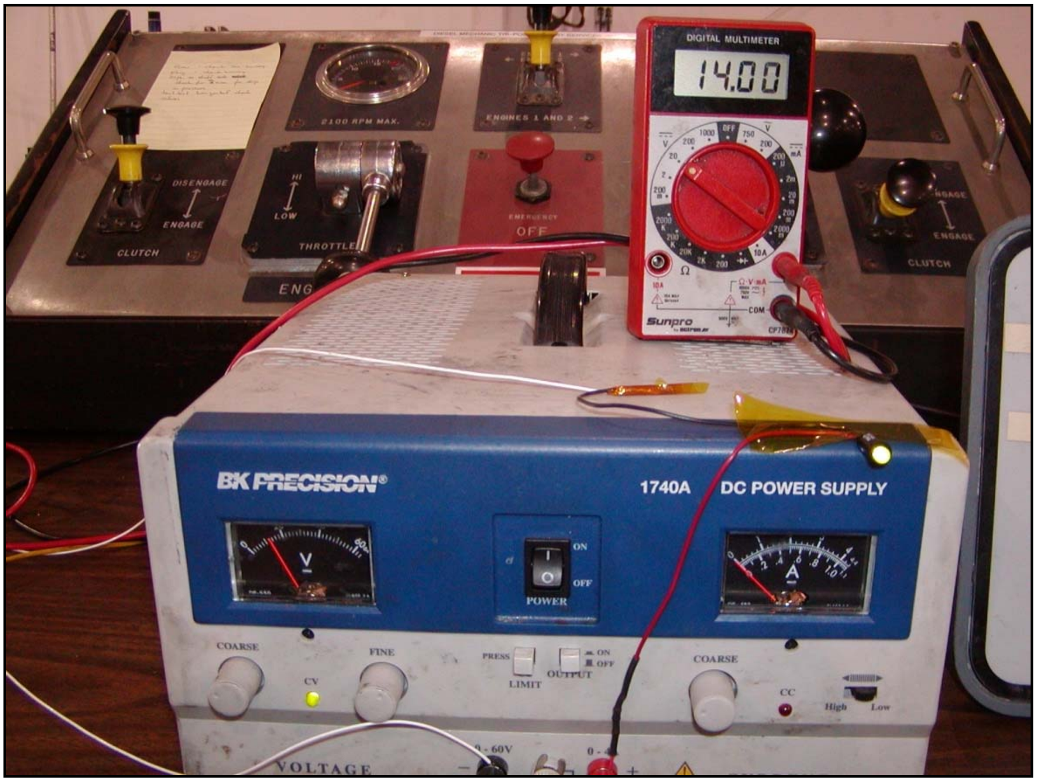

Figure 21. Monitoring of the electrical signal during testing

A total of 30 electrical cycles were run. These cycles consisted of turning power on with flow, holding the flow and pressure (at which electrical contact is made for a period of 5 minutes), followed by shutting electrical power off by either completely stopping fluid flow or reducing the flow rate to a level where the standpipe pressure falls below 200 psig. All tests were successful with no signs of leaks or any damage evident to the electrical contacts (bayonet and circular ring elements). During the break-in cycle the standpipe pressure required to make electrical contact ranged from 200 to 262 psig. Break in was accomplished in 15 cycles, after which 200 to 204 psig was consistently required to create an electrical connection between the bayonets and the contact rings. It is believed that the pressure differences before and after break in were due to seating in of the sealing elements. Table 7 summarizes these test cycles.

Table 7. Cycle Summary

Voltage	Pressure	Flow	Means of Breaking Electrical Continuity	Voltage	Pressure	Flow	Means of Breaking Electrical Continuity
14 Vdc	240 psig	226 gpm	Throttle	5Vdc		212	Throttle
14 Vdc	203 psig	216 gpm	Throttle	5Vdc		202	Throttle
14 Vdc	202 psig	212 gpm	Throttle	5Vdc		202	Throttle
14 Vdc	201 psig	212 gpm	Throttle	5Vdc		212	Throttle
14 Vdc	203 psig	216 gpm	Throttle	5Vdc		212	Throttle
14 Vdc	205 psig	230 gpm	Throttle	5Vdc	200 psig	203	DV
14 Vdc	250 psig	230 gpm	Throttle	5Vdc	200 psig	210	DV
14 Vdc	250 psig	230 gpm	Throttle	14Vdc	200 psig	212	DV
14 Vdc	250 psig	230 gpm	Throttle	14Vdc	204 psig	212	Throttle
14 Vdc	202 psig	211 gpm	Throttle	14Vdc	202 psig	200	Throttle
14 Vdc	264 psig	235 gpm	Throttle	14Vdc	200 psig	212	Throttle
5 Vdc	241 psig	228 gpm	Throttle	14Vdc	200 psig	212	Throttle
5 Vdc	220 psig	220 gpm	Throttle	14Vdc	200 psig	212	DV
5 Vdc	202 psig	212 gpm	Throttle	14Vdc	200 psig	202	DV
5 Vdc		202 gpm	Throttle	14Vdc	199 psig	210	DV

DV = Dump Valve

The bayonet/circular contact rings were successfully implemented and tested in three segments of composite drill pipe. The electrical connections showed unbroken electrical continuity and clean signals when energized with standpipe pressures slightly above 200 psig. The design modifications proved successful. However, this approach was abandoned because the components were too difficult to manufacture and there was not enough room in the tool joint design to accommodate them. The next activity was to pursue the ring/ring direct electrical connection.

6.3 Ring-to-Ring Direct Electrical Connection

The basic dual-ring design electrical connections for CDP are shown in Figures 22 and 23. The dual-ring design features no moving parts. Each component of the tool joint is modified to accept an insulated contact ring in the face of the tool joint. Each ring is attached to a conductor, which is passed through a portal machined in the wall of the tool joint. This portal terminates where the composite pipe attaches to the metal tool joint components. The insulated contact ring on the pin connection is machined to provide a pilot on the face. Thin O-rings are placed on both the inside and outside diameter of the pilot. The O-rings will mate with the flat face surface of the corresponding contact ring in the box connection of the tool joint. The purpose of the O-rings is to prevent any conductive material, such as copper-filled pipe dope, from contacting the mating surfaces of the contact rings. As the tool joint is made up, the O-rings make contact with the flat face conductor ring in the box connection slightly before the pilot face makes contact with the corresponding flat-faced contact ring.

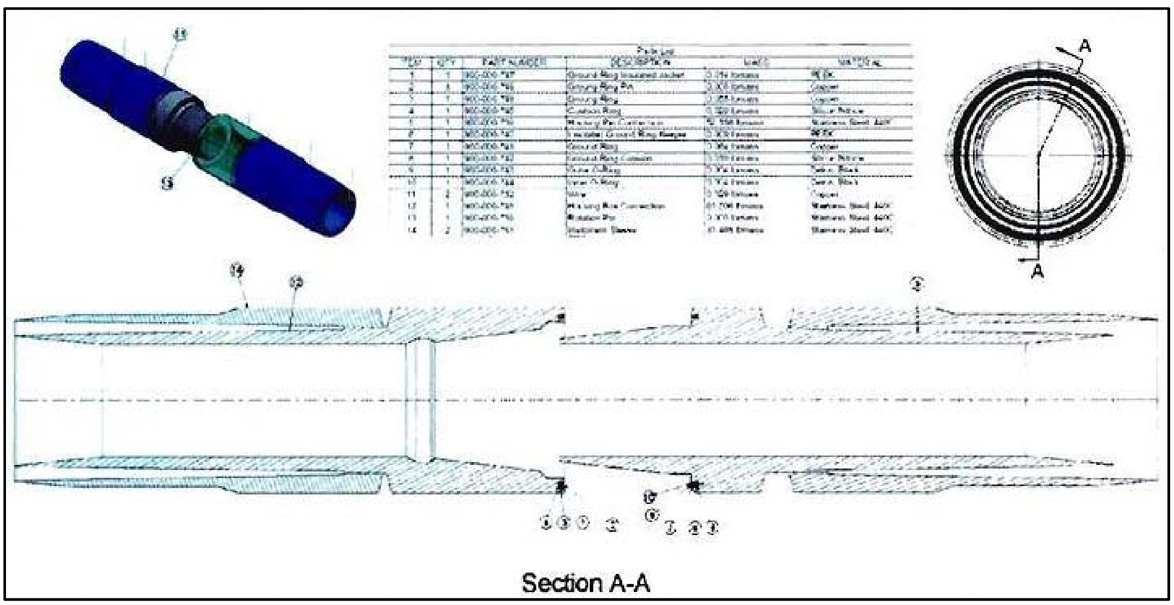

Figure 22. Dual ring electrical connection for CDP (2005 Annual Report)

Figure 23. Design of face contact assembly

6.4 Contact Ring Testing

Three tool joints were sent to Noble Downhole Technology for testing of the ring-to-ring contact. Some of the insulation was missing exposing the conductor on several of the as-received tool joints (Figure 24). The two parallel wires were measured and determined to be 25 AWG solid wire with a resistance of 16.5 ohms per 1000 feet at 77°F (19 ohms per 1000 feet at 149°F). The wires were separated and heat-shrink tubing installed on both. A small hole was tapped in each groove to facilitate grounding one of the wires to the tool joint sleeve. The wire for the tool joint box connection was too short, requiring a splice be made and drilling the wire feed hole deeper to allow clearance for the splice.

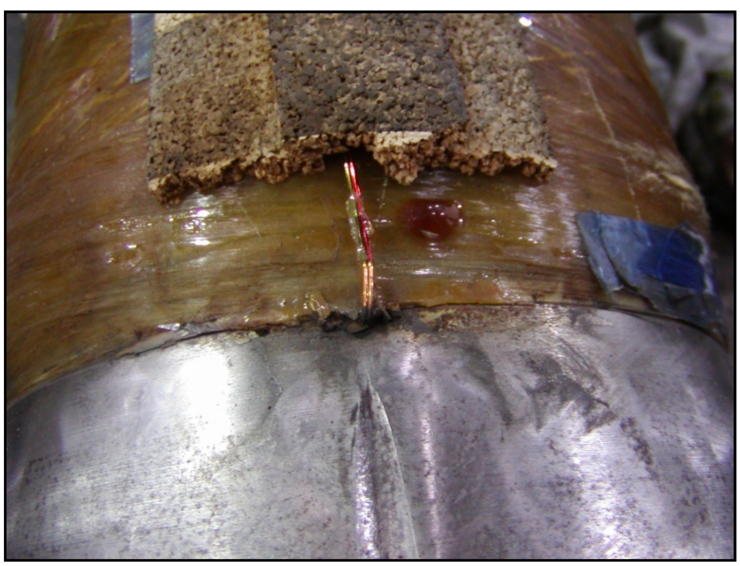

Figure 24. CDP as delivered showing exposed wire conductors

The molded contact rings were cemented in place with Loctite 480, which is a cyanoacrylate rubber toughened adhesive. The rubber seal lips were trimmed flush with the tool joint shoulder on each box connection. The molded contacts as-received were made approximately 0.020 inches taller than the drawing specifications requiring the sealed lips to be shaved down to specification before the tests could begin (Figure 25). All ring-to-ring contacts made connection when the tool joints were made up hand tight. Complete circuit resistance through the three tool joints was 1.1 ohms. Tool joints were torqued to 19,000 ft-lbs and left overnight (Figure 26).

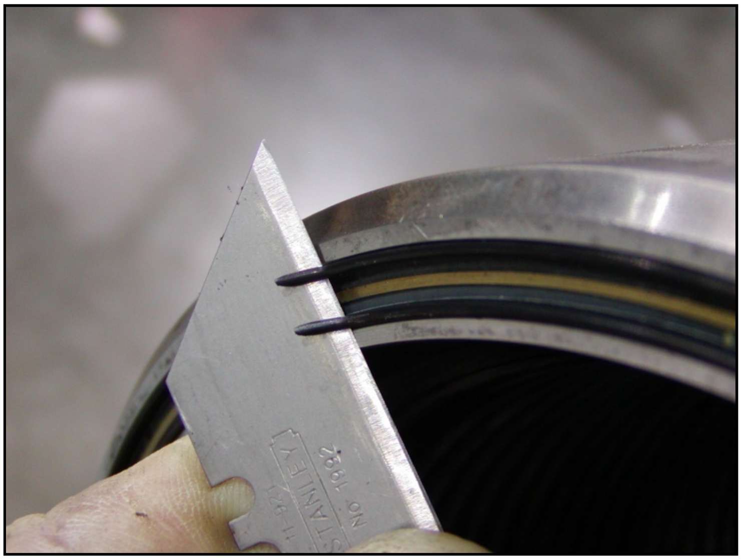

Figure 25. Shaving of out-of-specification seal lips

Figure 26. CDP made up to correct torque

The next morning the circuit was broken. The solder joint on tool joint no. 3 box connection was sheared and the wire no longer made contact. Similar types of problems had occurred during previous testing with a small pinhole in the solder connection allowing pressure buildup in the contact area to vent out. When the tool joints were torqued, the pipe dope trapped in the contact ring area apparently built up pressure during make-up and tore the poor quality solder (Figure 27) as there was not much solder holding the wire. A window was milled out and the wire reattached. The tool joint was reassembled and this time the solder connection on tool joint no. 2 Pin was sheared. The connection was repaired and the tool joint reassembled and connected at the proper torque. The same solder connection sheared again and was repaired a second time.

Figure 27. Example of poor soldering quality for wire connections

6.4.1 Data Signal Transmission

A 1,000 ohm resistor was placed on one end of the assembly and a 15 volt peak-to-peak sine wave signal applied across the three joints of composite drill pipe to examine the ability to transmit data signals. No attempts were made to match impedances.

Results are summarized in Figures 28 and 29. The data indicate that the ring-ring contact design does provide good data transfer characteristics, especially at frequencies at or below 500 KHz. This is well above the communication requirements of downhole MWD/LWD tools. Essentially no attenuation occurred below 100 KHz. Maximum attenuation was noted at 750 KHz measuring -3.6dB.

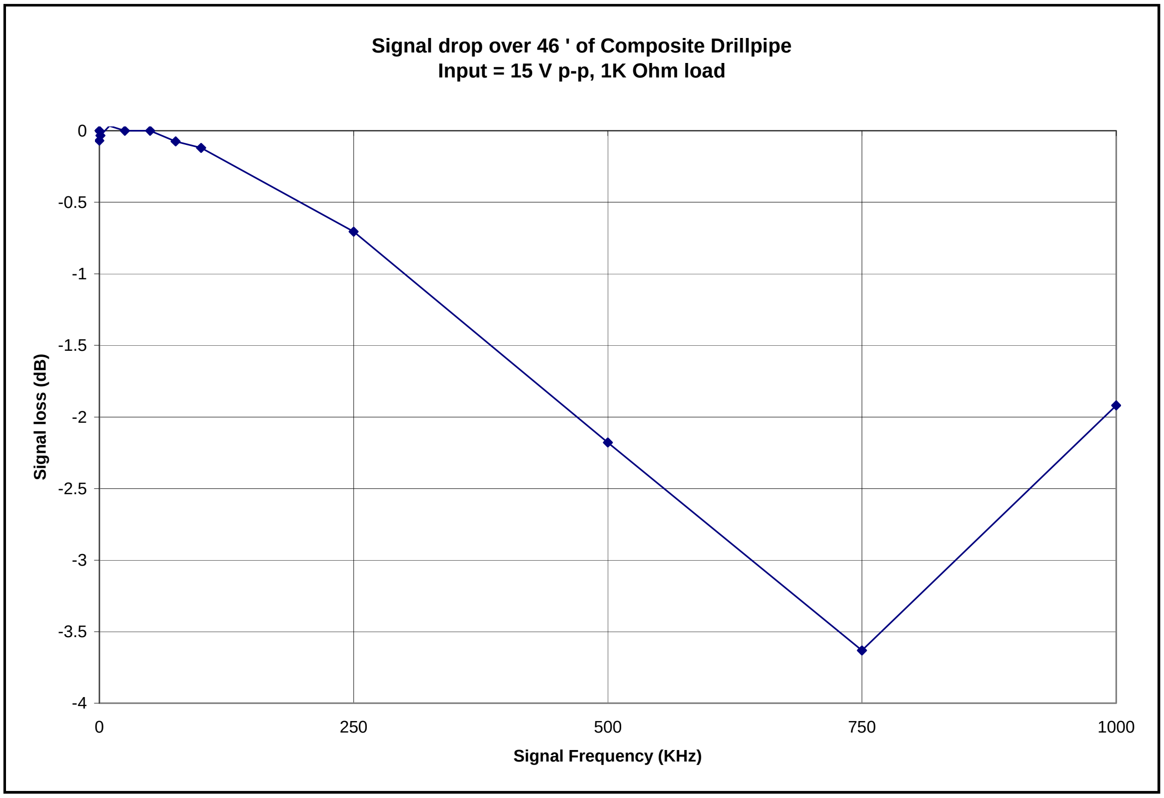

Figure 28. Data transmission testing results

6.4.2 DC Power Transmission

A 100 ohm power resister load was placed at one end of the assembly. Current was ramped up in increments to 25 watts. The power loss was minimal, averaging approximately 1% for the 46-foot long assembly, as shown in Figure 30.

6.5 Testing Recommendations

The composite drill pipe ring-to-ring contact can be made to effectively transmit electrical power and data signals from the surface to attached LWD/MWD bottom hole assemblies. This will require the following improvements in design and assembly procedures:

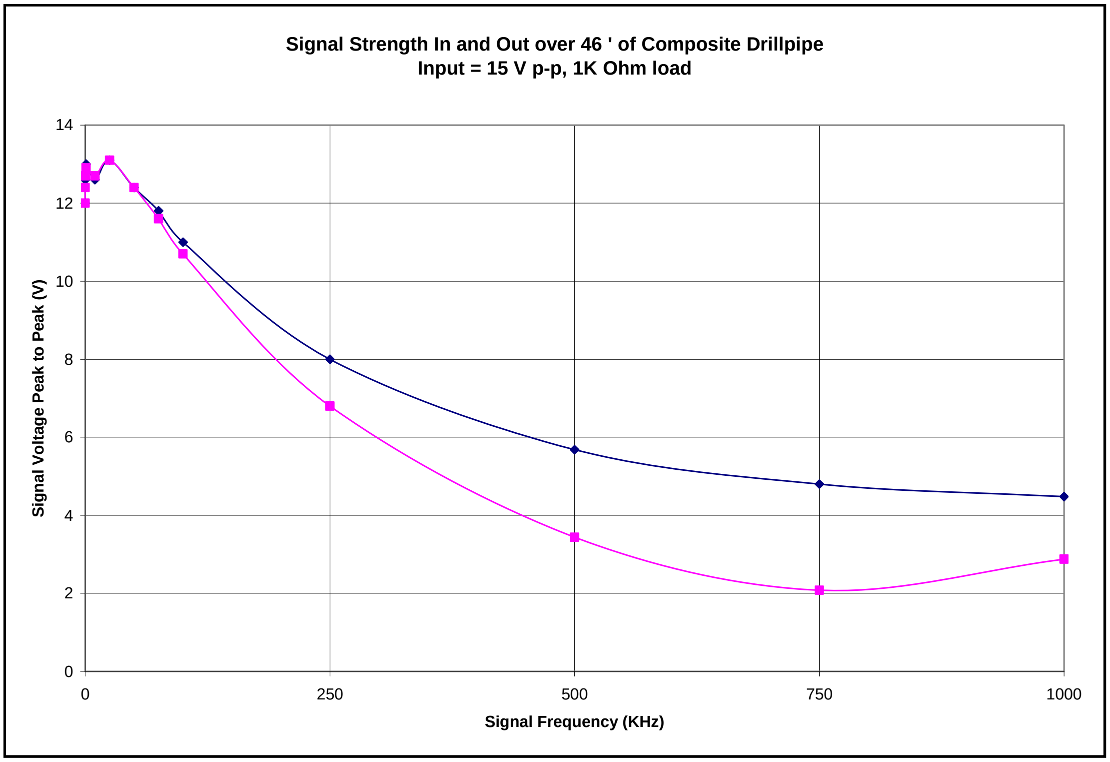

Figure 29. Signal voltages at distal end

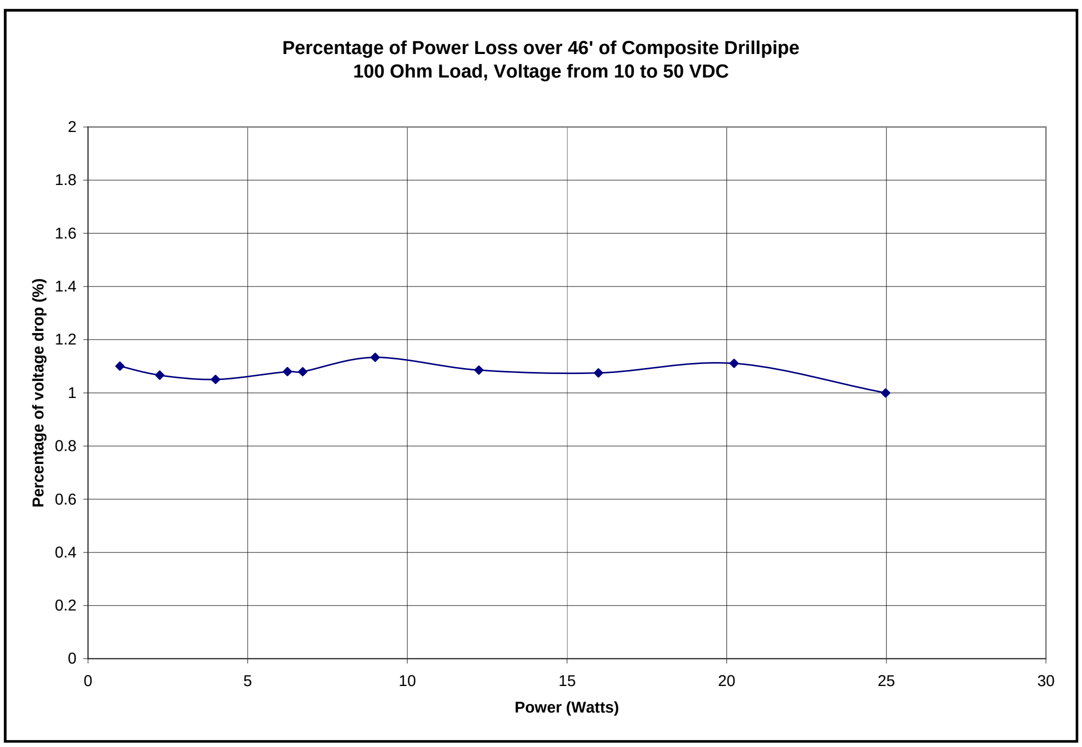

Figure 30. Power Loss percentage

- Wire protection during fiber wrapping is not sufficient to protect the wire insulation. This situation can possibly be improved by using a different type of wire insulation or embedding the wire deeper below the composite wrap.
- Wire attachment to the contact rings must be improved. A threaded solder cup would eliminate the failures due to poor solder quality (in the form of cold solder joints and failure to “pull” the solder through the depth of the metallic contact ring).
- Rubber elements must be made to design specifications. The requirement to shave off the excess lip height was believed to be responsible for lower than expected insulating properties shown by the decreasing resistance during torque make up.
- In actual field service, the wire size should be increased to 16 AWG as originally specified to decrease power loss.

7. Product Commercialization

The original project proposal assumed set-up of a manufacturing facility capable of producing 24 units of 30 foot lengths of 5 7/8 inch CDP per day. This plan was changed to allow modification of the existing equipment at Advanced Composite Products & Technology, Inc. (ACPT) to an acceptable pilot plant operation.

7.1 Pilot Plant Equipment

The following were accomplished toward developing the pilot plant:

- Winding of 10-foot sections of representative 5 7/8 inch CDP.
- A winding machine was modified to increase the winding length capability to handle full 30-foot sections (actual total length, shoulder to shoulder, of the metal joints is 31.5 ft.)
- A "curing cart" capable of curing four 30-foot sections simultaneously was added.
- A winding-curing cart designed for use with 3 3/8 inch CDP was obtained.
- A 30-foot lathe for final machining of CDP was acquired.
- The existing oven was capable of curing five sections of CDP simultaneously.
- A "Mandrel Puller" to extract mandrels from the 30-foot sections of CDP was designed and ordered.

The above basic facilities will allow "pilot plant" production of up to five 30-foot sections of CDP per day (possibly 10 to 15 with more upgrades and modifications). It is believed that this production rate will allow initial market evaluation. Additional capacity will require the incorporation of automation and continuous operation to the winding, curing, and machining functions. ACPT is working closely with Omsco to establish marketing levels and schedules. These results will determine the schedule and extent of pilot plant upgrade or the necessity to build a full-scale, continuous operation CDP production unit.

7.2 Commercialization

Following successful field testing, ACPT began offering the short radius composite drill pipe (SR-CDP) commercially to drilling companies. The first order was placed in January 2004 by Integrated Directional Resources (IDR) of Lafayette, Louisiana. IDR intends to use the pipe for drilling ultra short radius (USR) wells in the Gulf Coast. On location at one well in late July 2004, IDR reported problems with steel pipe failing while drilling a lateral section, and that they were using the composite pipe for all fishing operations (consistently pulling 20,000 to 25,000 pounds). As a result, IDR planned on using their entire stock of available composite pipe to complete the lateral section.

Following the commercial orders to Integrated Directional Resources (IDR), ACPT received an order from Torch International for 2000 feet of SR-CDP. The CDP was utilized for ultra short radius drilling for Petroleum Development of Oman (PDO). Several field failures of the pipe occurred leading to the development of ultra short radius composite drill pipe (USR-CDP) that was successfully tested by Torch International in Oman.

Fifteen joints of SR-CDP were sold to Maverick Energy for reentering wells in west Texas. All reports received were positive.

Twenty joints of the short radius CDP were sold to Grand Resources in 2006. Grand Resources had been using the CDP experimentally for the last five years in field operations and has now purchased more.

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