

Developing Improved Standards for Coiled Tubing

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Coiled tubing services grew rapidly from the mid-1980s to the mid-1990s, despite the downturn in the oil and gas industry. This growth has accelerated with the recent upturn. What new research is required to maintain standards and support the growth of this technology?

Oilfield engineers have long dreamed of a reliable, continuous pipe that could be run in and out of wells at high speed without the need to stop for connections. Efforts to make this dream a reality have resulted in products such as flexible pipe (made of alternating layers of wound steel wire armor and plastic sheathing) and coiled tubing (rigid reeled steel pipe). First developed in the 1960s, growth of a coiled tubing (CT) services industry was stunted during the first 25 years of its existence due to the fact that the pipe, though it met the requirement of being continuous, often failed the requirement of being reliable.

Gas Research Institute (GRI) has actively supported efforts to accelerate the application of CT technologies, particularly where they can reduce the cost of natural gas production. Among other advantages, coiled tubing drilling holds promise for reducing the cost and increasing the efficiency of developing low pressure and marginal gas reserves through small-diameter, underbalanced drilling.

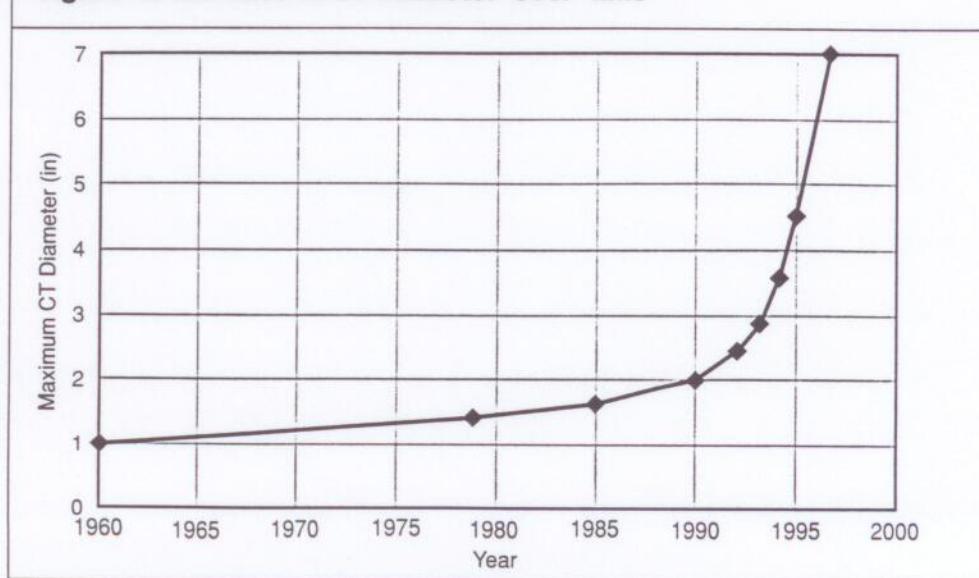
Early Improvements Helped Support Growth

In the mid-1980s, significant improvements were made in both the manufacturing of CT and in the understanding of its mechanical properties and limitations. These advances improved CT reliability, stimulating the expansion of CT applications. Because CT services are often more economical than the snubbing, slickline or workover

services they replace, the CT services industry actually benefited from the downturn in the oil and gas industry during the late 1980s and early 1990s, as cost-cutting operating companies searched for more economical solutions to their workover problems.

During the 1985-1995 decade, CT manufacturers continued to make improvements in the quality and size of the pipe (Figure 1). GRI, along with

Figure 1: Increase in CT Diameter Over Time



joint industry participation, aided in these improvements by funding research that improved the understanding of the CT welding process and thus the reliability of CT welds (Newman *et al.*, 1995a; Newman *et al.*, 1996a). Equipment manufacturers also improved the quality and capability of the equipment used to provide CT services. Service companies developed new service techniques for cementing, logging and open-hole drilling with CT. GRI also funded a feasibility study of an electric drilling motor that is currently being developed in Europe (Newman *et al.*, 1995b; Newman *et al.*, 1996c).

Continued Growth Highlights Need for Standards

The upturn in the oil and gas industry of the past several years is driving CT technology to new heights, and the envelope of CT services considered reliable by the industry is being expanded, placing greater and greater demands on the CT pipe. In any rapidly growing industry there is always a concern about things getting "out of control," and it is generally recognized that some degree of regulation and standardization is needed to avoid disasters and improve efficiency. However, too much regulation and standardization can stunt the growth of an industry.

GRI, together with the International Coiled Tubing Association (ICoTA), is continuing to fund projects that improve the understanding of the reliability limits of the pipe and support the development of CT standards that are welcomed by the industry (Newman *et al.*, 1996b; Newman *et al.*, 1997). This effort began with a study of the industry's needs and priorities regarding standards (Knowles *et al.*, 1995). A CT Welding Standard (based largely on the weld research mentioned previously) and a CT Pipe Manufacturing Standard are the first two standards to be

completed as part of this effort. The Society of Petroleum Engineers (SPE) has agreed to publish these standards for ICoTA. The ultimate goal is for these standards to become accepted as American Petroleum Institute (API) and International Organization for Standardization (ISO) standards.

The development of these standards has not been simply a bureaucratic exercise; it has very practical implications as well. In the absence of a CT manufacturing standard, each operating company is forced to develop its own. This results in a substantial burden for the CT manufacturing and service companies faced with meeting multiple standards for multiple customers. An industry accepted manufacturing standard should eliminate this problem. Likewise the weld standard should improve the quality of field butt welds (the most unreliable element of CT strings) by aiding service companies in setting internal requirements for both welder and weld.

Applications for CT Expand

Demands of the marketplace are expanding the applications for CT. Three areas in particular are the scene of increased CT activity: high pressure applications, flowline applications, and drilling applications.

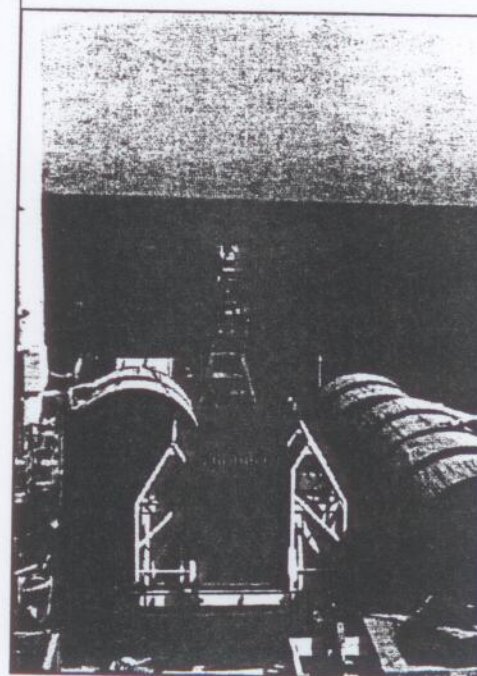
► **High Pressure** - For many years CT operations were limited to wells with wellhead pressures less than 3000 pounds per square inch (psi), while pumping pressures were limited to 5000 psi. In recent years this operating envelope has been pushed to include wells with wellhead and pumping pressures as high as 10,000 psi. Increased pressure limits have allowed sand cleanout operations to be performed in high pressure gas wells without the need for hydraulic workover (snubbing) systems. Accordingly, the cost of these operations was reduced by

more than 50 percent, and the average time required to perform the operation reduced from 9 days to 1 day, allowing 8 additional days of production. The cost savings for the natural gas industry due to this service capability alone is estimated at over \$15 million per year.

► **Flowlines** - With CT diameters up to 6 5/8 inches now available, and with the development of external plastic coatings, CT flowlines are becoming increasingly popular alternatives. Although the actual cost of the CT flowline itself is about the same as the cost of jointed flowline, the cost of installation is significantly reduced. One of the largest markets for CT flowline is the Gulf of Mexico where it is currently seeing widespread use, primarily for natural gas and methanol (Figure 2).

► **Drilling** - Since its inception in 1991, CT drilling (CTD) technology has advanced rapidly (Figure 3). Though still a small percentage of the overall drilling market, CTD has found niche markets in which it has a significant economic advantage (see sidebar).

Figure 2: Installation of 4 1/2 Inch OD Coiled Tubing Flowline



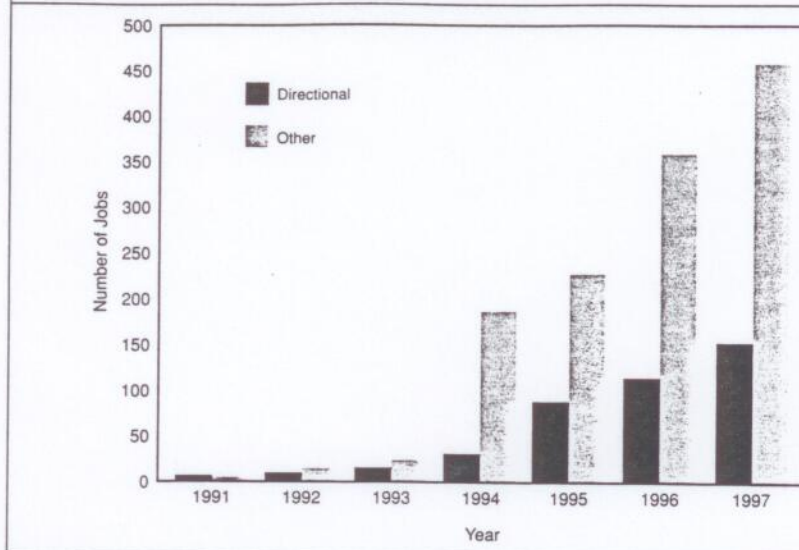
Directional drilling systems as small as 2 7/8 inches outside diameter (OD) have been developed for through-tubing drilling. Window cutting systems and through-tubing whipstocks have been developed. Measurement-while-drilling systems allow the monitoring of pressure for underbalanced drilling and measurements for geosteering.

Pipe Fatigue: A Drilling Constraint

Drilling is the most demanding of all of the new CT services because it involves large diameter pipe (2 inch through 3 1/4 inch OD) operating at high internal pressure with repeated cycling (as weight is picked up and set down on bit). This cycling fatigues the pipe quickly, reducing its life span (in some cases to a single drilling operation).

Some major equipment innovations have been made to reduce fatigue damage. For example, the Chameleon CT Drilling System™, developed by Transocean Ensign Drilling in Canada reduces fatigue damage by

Figure 3: Increase in Annual Number of CT Drilling Jobs



approximately 66 percent by eliminating the guide arch above the injector (Figures 4 & 5). Alternatively, the CT reel is held above the injector and the CT feeds off vertically downward into the injector. A similar unit has been designed where the entire injector and reel assembly will be able to rotate at low speed (5 rpm). When completed in

mid-1998, it will be the first CT unit with the ability to rotate the tubing.

The *Galileo II CT Drilling Barge* developed by Baker Hughes INTEQ for use on Lake Maracibo, Venezuela, is designed to reduce fatigue damage in two ways (Figure 6). First, the reel is 24 feet in diameter, allowing a larger bending radius than smaller

► Advantages and Disadvantages of Coiled Tubing Drilling

ADVANTAGES

- No drill pipe connections**
Faster trip time
Less mud spillage (environmental advantage)
No pipe handling (safety advantage)
No pressure bleed off for connections with compressible drilling fluids (foam, N₂, air)
- Smaller location size** (environmental and cost advantage)
- Less equipment** - easier mobilization and demobilization
- Better pressure control**
Safer underbalanced drilling
Increased ROP
Decreased formation damage
Less concern with kicks
- Ease of automation**
Better weight-on-bit control
Remote drilling - no personnel at wellhead
- Better suited to telemetry technologies**
Electric line can be installed inside the CT for high speed data and electrical power
Drilling fluid pressure pulse telemetry has less noise in the signal

One question often asked is: "Why use CT to drill instead of a conventional rig?" The answer to this question is different for different drilling applications. In fact, there are many drilling applications for which CT is neither technically nor economically suitable. The following list gives the advantages and disadvantages of coiled tubing drilling. If a CT application does not capitalize on one of these advantages, and conventional rigs are readily available, CTD will probably not be justifiable.

DISADVANTAGES

- Small diameter** (2 to 3 1/4 inches)
Limited hole sizes
Limited mud flow rate
- Cannot rotate from surface**
Slide drilling
Orientation tool required
Motor drilling
- Large, heavy reel** Often difficult to transport and lift

conventional reels. Secondly, there is a small ejector located at the levelwind of the reel, which ejects the CT into a parabolic arch that ends at the top of the injector. This arch effectively eliminates the guide arch, which would typically be located above the injector.

New Applications Prompt Need for Research

The new services and capabilities demanded by the marketplace are prompting additional research to expand the reliability and capability of CT in a manner that keeps pace with these demands.

For example, the repeated bending that occurs as CT is unbent from the reel, bent around the guide arch and then unbent going into the well, is a unique requirement for steel pipe. A photo of a typical land CT operation shows the bending of the CT as it comes off of the reel and travels over the guide arch above the wellhead (Figure 7). The author is unaware of any other application for steel pipe where it is plastically bent and unbent repeatedly and expected to maintain its structural integrity. This repeated bending has several undesirable effects (Table 1).

Currently, the operating limits used to determine the maximum pressure and axial load that can be applied to CT are based on the von Mises incipient yield criteria (Juvinal, 1967), a criteria that has been used for many years to determine the operating limits of conventional oilfield tubulars. However, this criteria does not take into consideration any of the effects mentioned in Table 1. The von Mises incipient yield criteria is employed to determine when a material without residual stresses would reach its yield stress assuming that its wall thickness and diameter have not changed. This is obviously unrealistic when applied to CT.

Table 1: Effects of Repeated Bending on Coiled Tubing Strings

- 1. Residual Stresses** - Internal residual stresses left over from its bending history can cause the pipe to yield much earlier than a material without these stresses. They can also cause the pipe to curve when no axial load is applied.
- 2. Baushinger Effect** - New steel has a clearly defined yield stress at which the material changes from being deformed elastically to being deformed plastically. After repeated plastic cycling the stress-strain relationship changes and the point of yielding can no longer be clearly defined.
- 3. Work Softening** - Repeated plastic cycling reduces the strength of the material.
- 4. Permanent Deformation** - During its life, the CT grows in diameter, becomes oval in cross section and elongates (Newman *et al.*, 1997). In some cases a string must be scrapped before reaching the end of its fatigue life because its diameter has increased to the point that it will no longer operate in the surface equipment. After a single trip in and out of a well, a typical string will have been lengthened about 10 feet, and this elongation continues during the entire life of the string. If a typical string makes 50 trips during its life, the total elongation may be 500 feet.
- 5. Rotation Effects** - When being removed from a well, CT is usually in a different rotational orientation than when it was run into the well. This rotation is one of the most significant factors affecting axial elongation.
- 6. Effects of Axial Load While Bending** - During operation, the reel pulls against the injector, causing an axial load on the CT while bending both at the reel and at the injector. This axial load is a second factor that (according to theory) causes significant axial elongation.

Figure 4: Chameleon CT Drilling Rig

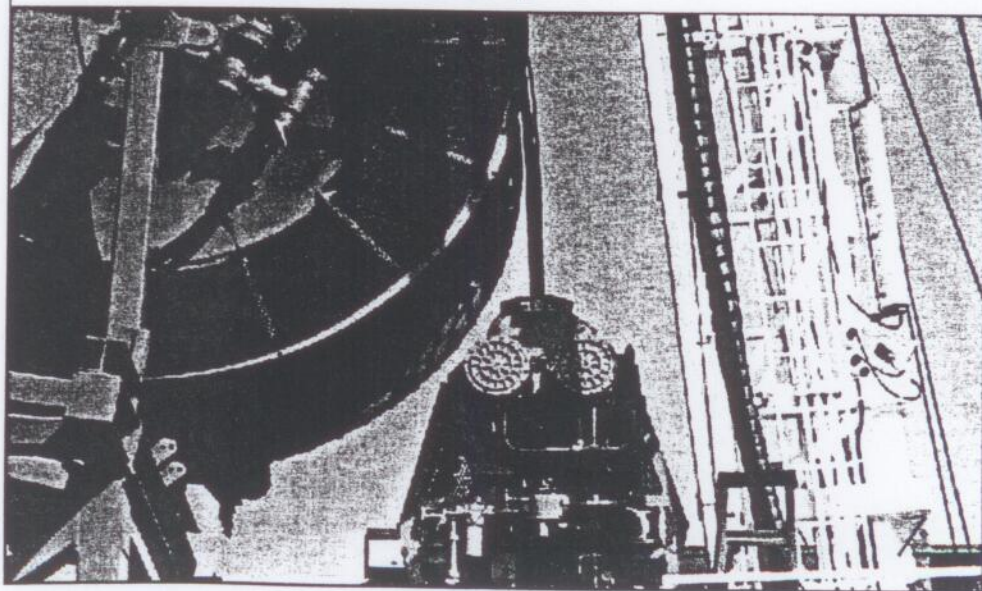
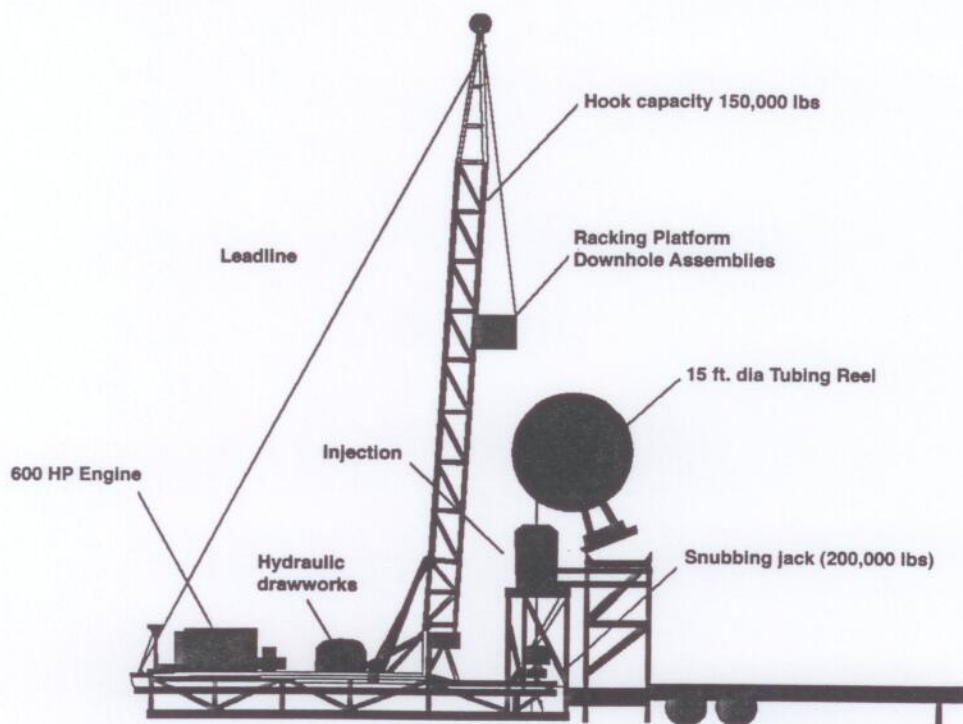


Figure 5: Schematic of Chameleon CT Drilling Rig



Research is needed to determine the real operating limits of CT. This research should involve study of the plastic behavior of CT and the resulting changes in its material characteristics.

Engineering models can then be developed to predict CT behavior and software can be developed based on these models to predict permanent deformation (elongation, diametrical growth, wall thinning) and modified material characteristics. More realistic CT limits can then be set based on these values (Newman *et al.*, 1996b).

Past and Future Research Efforts

A significant amount of research has already been done through GRI and joint industry cofunding. The results of this effort include:

- Measurements of the Baushinger affect on an entire CT cross section
- Measurements of the work softening during repeated cycling
- Development of a uniaxial model of the elongation of the CT
- Validation of the uniaxial model with lab testing
- Triaxial modeling of the CT plasticity including diametrical growth and ovalness.

This work revealed that two additional effects (items 5 and 6 in Table 1) must be considered when attempting to model CT behavior: The uniaxial model showed that the effect of rotation is one of the most significant factors affecting axial elongation, followed by the effect of axial load while bending.

Unfortunately, CT test equipment currently in use is unable to simulate

Figure 6: Galileo II Drilling Barge

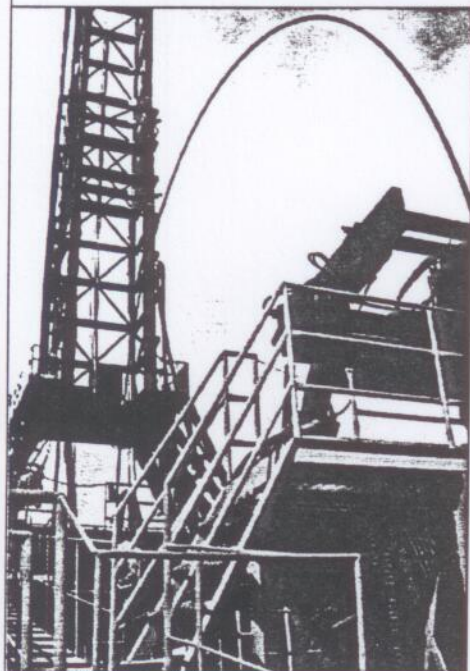
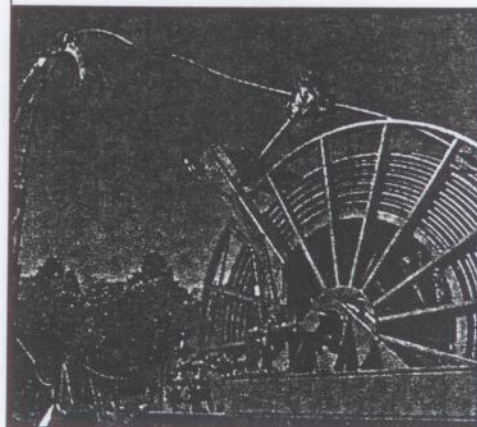


Figure 7: Bending of CT During Operation



these two additional phenomena, making it impossible to verify the theoretical implications and develop the appropriate models. A new CT Test Machine (CTTM) currently being built will allow testing of all critical parameters.

With the new apparatus, a CT sample is held between a curved form and a straight form (Figure 8). The forms are moved up and down, causing the CT to repeatedly bend and straighten. The end fixtures are designed to permit the application of an axial load during the bending cycle and also to permit rotation of the CT when straight. Internal pressure can be maintained at a preset level while these actions are carried out.

Once completed, the apparatus will be used to validate the triaxial model. Further testing will be done to determine the effects of axial loading and rotation on fatigue life, and possibly also to determine the effects of H₂S exposure on CT limits.

Plan for New Standards Development

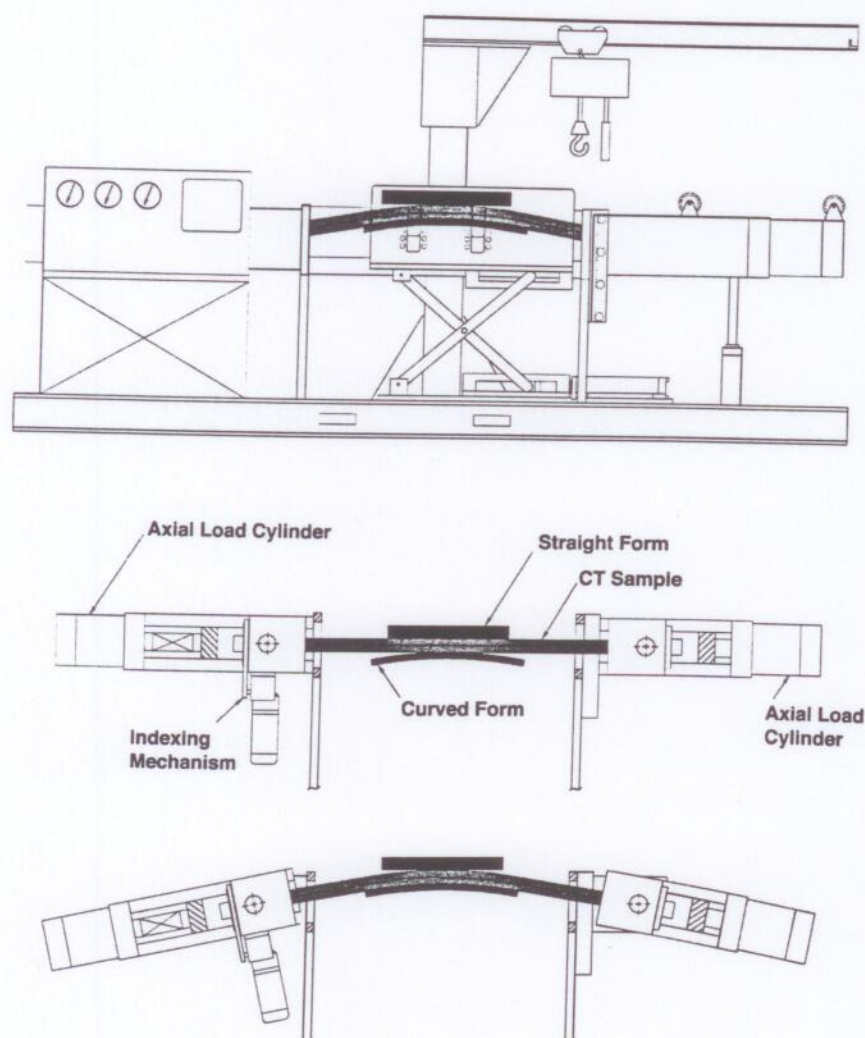
Results from the weld research have already been used to develop a welding standard and are available (*"Slimhole and Coiled Tubing Standards, Phase I - Weld Technology,"* GRI Final Report, GRI-95/0500. The standard is expected to be published by SPE in early 1998. A new CT pipe specification should be

completed in the first quarter of 1998 and will also be available from SPE.

Benefits To The Gas Industry

The standards developed during this project should reduce the incidence of CT failure and help to avoid the premature replacement of CT. Together, these outcomes will reduce the overall cost of CT drilling, allowing it to be more widely applied in the development of low pressure and marginal gas reserves. These types of accumulations stand to benefit the most from technologies that permit safer, lower-cost underbalanced drilling in damage-prone formations, or technologies that permit quick, precise deviated drilling. GRI support is enabling the CT industry to continue to expand in these areas. ■

Figure 8: Schematic of CT Test Machine



For more information on GRI's role in CT technology, contact Steve Wolhart, GRI Principal Project Manager, Drilling & Completion, at 773/399-8278 or via e-mail at swolhart@gri.org, or Ken Newman, CTES, L.C., at 409/521-2203 or via e-mail at knewman@ctes.com.

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