GasTIPS®

Fall 2002
Volume 8
Number 4

Technology Developments in Natural Gas Exploration, Production and Processing

A Publication of Gas Technology Institute, the U.S. Dept. of Energy and Hart Publications, Inc.

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GTI-02/0185

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GasTIPS® (ISSN 1078-3954), published four times a year by Hart Publications, a division of Chemical Week Associates, reports on research supported by Gas Technology Institute, the U.S. Department of Energy, and others in the area of natural gas exploration, formation evaluation, drilling and completion, stimulation, production and gas processing.

Subscriptions to ***GasTIPS*** are free of charge to qualified individuals in the domestic natural gas industry and others within the western hemisphere. Other international subscriptions are available for $149. Domestic subscriptions for parties outside the natural gas industry are available for $99. Back issues are $25. Send address changes and requests for back issues to Subscriber Services at Hart Publications, 1201 Seven Locks Road Suite 300, Potomac, MD 20854, FAX: 301/424-7260. Comments and suggestions should be directed to Karl R. Lang, ***GasTIPS*** Editor, at the same address.

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POSTMASTER: Please send address changes to ***GasTIPS***, c/o Hart Publications, Inc.,
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Comments

New Applications Blur the Boundary Between Upstream and Downstream

This issue of *GasTIPS* includes two stories related to liquefied natural gas (LNG), not a typical topic for a journal that purportedly focuses on natural gas exploration, production and processing technologies. LNG plants are part of the transportation business, right? Perhaps not forever. One of the stories, *Thermoacoustics for Liquifaction of Natural Gas,* highlights a technology that may some day make LNG technology applicable on a smaller scale. The goal is finding a way to use gas liquefaction to economically produce remote gas accumulations that, while significant, won't support a multi-billion dollar LNG project. The same sort of approach is being pursued for another three-letter acronym: GTL. Companies like *Synfuels International* of Dallas, Texas, are working on technologies that will permit a skid-mounted, portable, Fischer-Tropsch gas-to-liquids system to convert as little as 10, 25 or 50 MMcfd into easily portable barrels of liquids, consuming an economically reasonable percentage of the gas in the process. If these technologies can eventually be commercialized, GTL and LNG "equipment" may become simply additional options for upstream "processing" of natural gas, rather than downstream destinations. In any case, when technologies relate to finding ways to economically produce more gas, we will include them in *GasTIPS.*

The rest of the issue includes stories on a novel approach to fracturing, an ultra-lightweight cement formulation, and a summary of attempts to build a temperature-tolerant MWD tool. We also present the results of a series of workshops held during the past summer that gathered industry input on what research will be needed to double the contribution of unconventional gas resources to the nation's energy supply over the next decade.

We hope you'll find this issue of *GasTIPS* informative. Please contact the individuals listed at the end of each article to obtain more information on specific topics. If you have any questions or comments, please contact the Managing Editor, Karl Lang, at klang@chemweek.com/.

The Editors

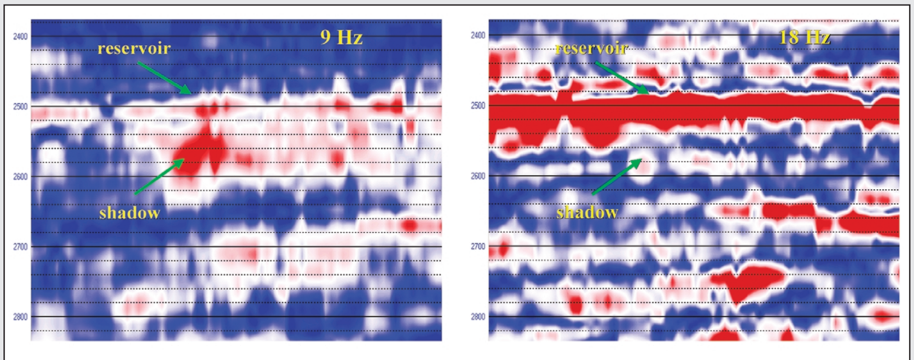

Figure 4: ESP Instantaneous Amplitude Sections at 9 and 18 Hz for Another Gulf of Mexico Reservoir

Correction:

Figures 3 and 4 on page 26 of the Summer issue of *GasTIPS* were incorrect. The correct figures are shown here. A full-sized pdf of the correct version of the entire article (*The Use of Spectral Decomposition as a Hydrocarbon Indicator*) may be downloaded from the Summer issue of *GasTIPS* located online at the NETL website at http://www.fetc.doe.gov/scng/index.html (under Reference Shelf, E&P, Technical Journals).

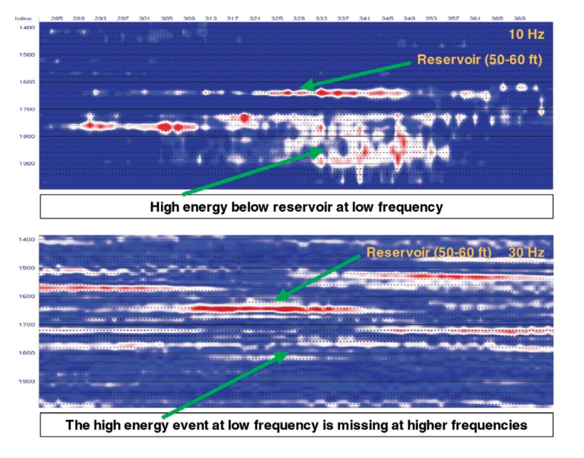

Figure 3. ESP Instantaneous Amplitude Seismic Sections From a Thin Gulf of Mexico Reservoir at 10 and 30 Hz

Our apologies to the authors and the readers for any confusion caused by this error.

Ultra-Lightweight Cement Slurries Improve Cement Performance

By Fred Sabins
Cementing Solutions, Inc.

Cementing systems using ultra- lightweight hollow spheres can improve lightweight cement performance in deepwater operations and provide a viable alternative to conventional lightweight cement slurries.

In today's critical deepwater wells, the use of ultra-lightweight cementing systems could improve well performance by enhancing zone isolation and reducing cementing failures. Many deepwater operations, especially in the Gulf of Mexico (GOM), are characterized by unique conditions that require high-strength, lightweight cements capable of withstanding cycling stresses for extended periods of time.

Results of a recent Department of Energy (DOE) project demonstrate that ultra-lightweight cement slurries using new ultra-lightweight hollow spheres (ULHS) provide higher compressive strengths at lower densities and outperform conventional lightweight cement slurries in long-term durability.

Based on an industry survey conducted by Westport Technology Center in 1997, an average 5 percent of total well costs were spent on cementing (total industry expenditure of $1.8 billion/year), and the average failure rate of cementing jobs was 15 percent. For these cases of failure, cementing costs rise to 17 percent of total well costs. These costs amount to an estimated $470 million/year to repair cementing failures. About one-third to one-half of these failures could be prevented with an effective lightweight cementing system.

In this project, *Cementing Solutions, Inc. (CSI),* sponsored by the DOE's National Energy Technology Laboratory and industry representatives, studied the effects of using ULHS to improve cementing systems, and the ability of ULHS to provide improved cement performance. The objective of the project was to develop cementing systems using ULHS for deepwater and other critical applications, test the physical performance of the cement slurry, and compare test results to the performance of conventional lightweight cements. Results demonstrate that ultra-lightweight cements exhibited high strength, low permeability, easy slurry designs, and durability.

Limitations of Conventional Lightweight Cements

Conventional lightweight cements typically use water as the lightweight agent to decrease density, and include materials that absorb the water and keep the slurry and cement homogenous. These conventional cements, though low in cost, exhibit some severe drawbacks; they achieve very low compressive strengths and have difficulty providing long-term zone isolation under severe stress conditions. In addition, these cements have a minimum density limit of 11.5 lb/gal.

Conventional hollow glass spheres have been used to achieve densities as low as 9.5 lb/gal, however, they are limited in application because of the low crush strength of the beads under pressure. This factor limits the use of these products in many applications.

Foam cements using nitrogen are commonly applied to prevent lost circulation in low-pressure reservoirs, but foam cements have high permeability and low strength, resulting in cementing failures and higher completion costs. In foam cement, nitrogen-filled void spaces can connect to form passageways that allow fluid migration through the cement, leading to cement failures. Additional limitations often seen with foam cements include: higher friction in the well (which can lead to lost circulation), inconsistency in application, difficulty in controlling the cementing job at the surface, lack of quality assurance, and the inability to measure bond strengths with sonic and ultrasonic evaluation tools. Despite these problems, foam cement slurries are currently the industry preference for attaining acceptable densities during critical cement operations.

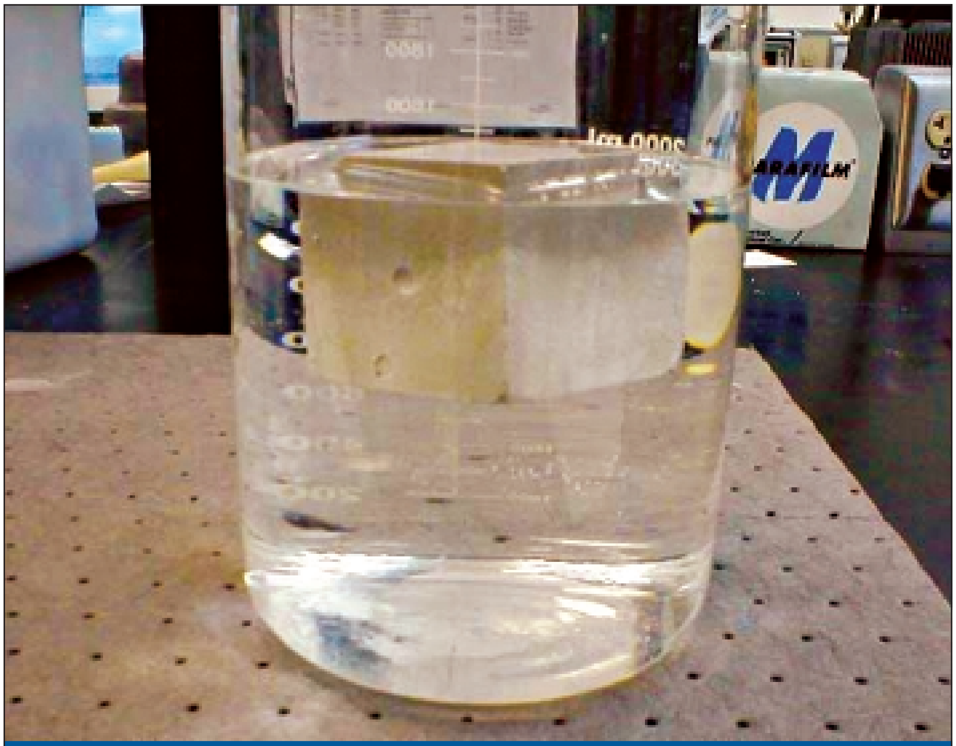

Figure 1: ULHS Slurries Exhibit Densities Less Than Water

Technology Advances in ULHS

Although efforts to improve the quality of zone isolation through the use of lightweight foam slurries have made progress, current data indicates a continuing problem in maintaining a long-term seal with conventional cementing systems. The U.S. Minerals Management Services estimates that 11,000 out of 14,000 producing wells in the GOM have gas pressure on one of the annuli. This figure amounts to more than 70 percent of the producing wells in the GOM. Ultra lightweight cement slurries could significantly increase the success of cement jobs in critical applications.

Although lightweight hollow spheres have been used in the industry for some time, recent technology advances have improved the hollow spheres to be ultra-lightweight, while exhibiting superior crush strengths of 3,000 to 10,000 psi. These ULHS can attain a specific gravity of as low as 0.32 to 0.46 (Figure 1), while resisting wellbore pressures as high as 6,000 psi (Figure 2). While traditional lightweight hollow spheres have achieved low specific gravities (0.67), they fail to withstand high pressures, collapsing in higher-pressure operations. This limits their application to more shallow wells. An added benefit is that ULHS cement slurries are easy to design, mix, and pump.

Project Data and Results

The project team for this effort combines some of the best industry expertise to ensure that the data collected has the widest possible applicability. The project steering committee, comprised of operating companies, service companies, and materials and equipment suppliers, includes representatives from *ExxonMobil, Shell, BJ Services, Halliburton Energy Services, Schlumberger, 3M* (ULHS supplier), *TXI* (cement supplier), and *Chandler Engineering* (laboratory equipment supplier). The $1.13 million, two-year project was funded in part by DOE ($670,000) and in part through industry cost shares ($460,000).

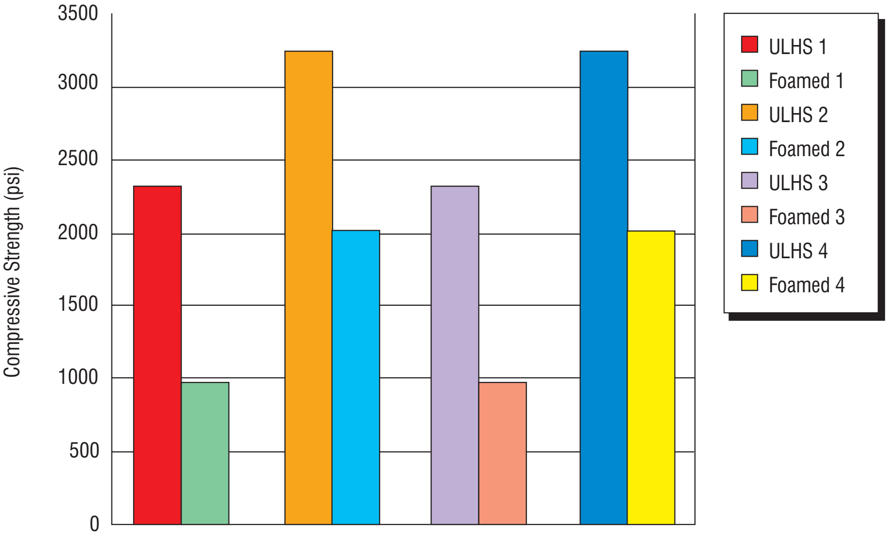

Figure 2: Foam vs. ULHS Compressive Strength Testing at 10.0 lb/gal and 11.5 lb/gal for Four Different Test Conditions

To ensure that the results obtained provide significant value to the industry, the tests were designed and applied to conditions drawn from more than 5,000 data points from field jobs in the U.S. supplied to *CSI* by service companies. *CSI* used these data to determine the conditions under which lightweight cements are most commonly used, as well as to define the type of operations currently being performed in deepwater wells.

In addition to standard testing of cementing slurries containing ULHS, *CSI* performed a unique combination of tests to measure a slurry's ability to withstand formation stresses over long periods of time. Although the mechanical properties of formations are commonly tested, the same mechanical properties tests are not commonly used to test cement. Triaxial load was applied to the samples to simulate wellbore conditions, and the samples were also tested for Young's modulus and tensile strength.

Stress cycling tests were also performed to ensure that the ultra-lightweight cement slurry could withstand the changes in temperature that occur within deepwater wells. Stress cycling within a well can cause the cement-to-pipe bond and ultimately the cement seal to deteriorate. Test results using the ULHS slurry indicated that the slurry could withstand cycling temperature changes of 135°F.

Additionally, special test cells were designed to test the cement's shear bonding capability in both the hard formations typically found on land, as well as in the soft formations common to deepwater wells in the GOM. To prove the value and strength of ULHS, *CSI* had to ensure that ULHS could withstand the stresses found in both types of formations. In both cases, test results indicated that the ULHS slurry could withstand a differential pressure stress of 5,000 psi.

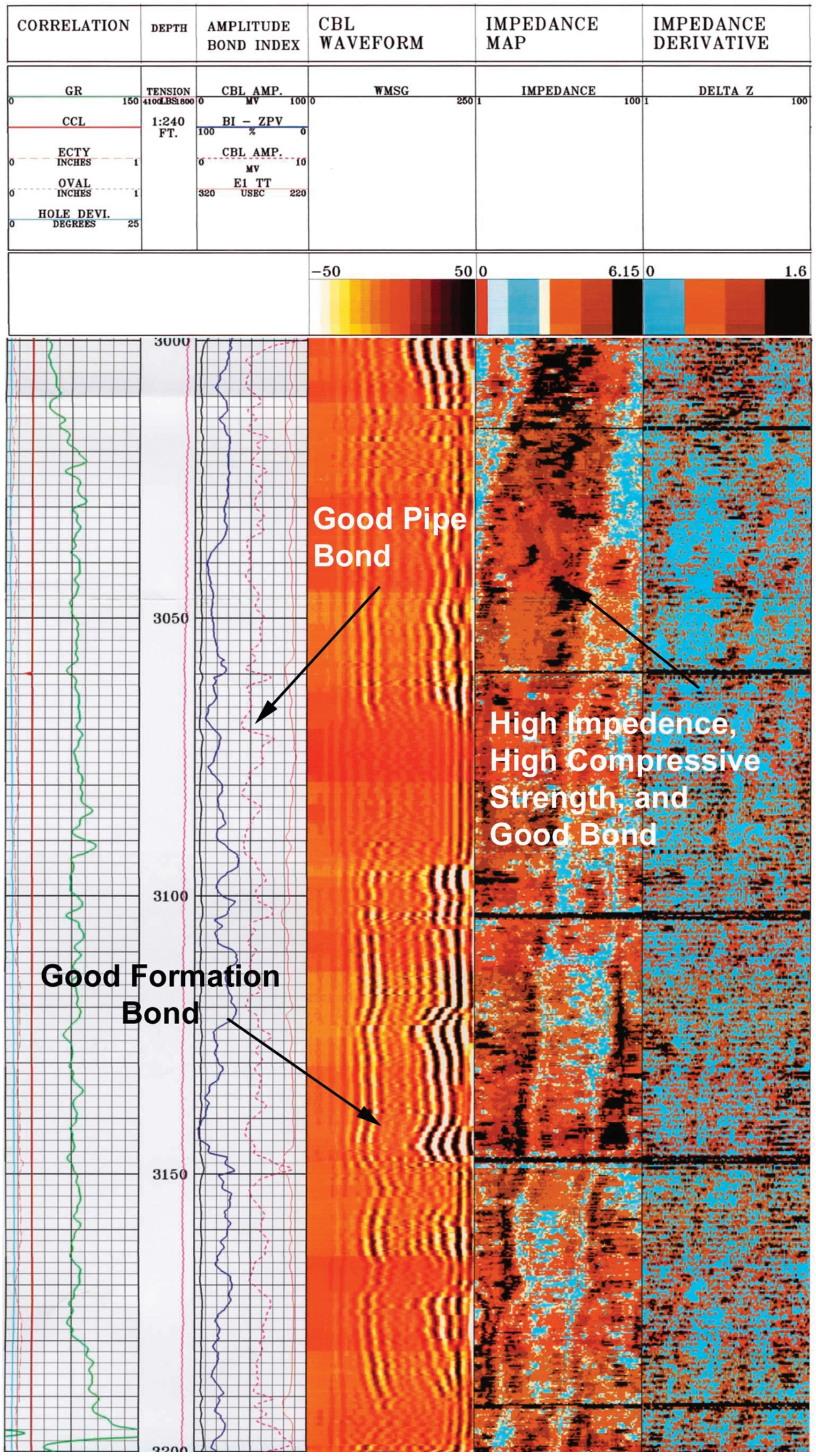

Figure 3: CBL and Ultrasonic Log for 10 lb/gal ULHS Slurry

Field Test Results

Two field tests were designed to test the slurry's performance in actual formations. The first field test was designed to ensure that the slurry could be easily blended, mixed, and pumped on location with little trouble. The second field test was designed to test the slurry's performance in a land-based well that closely resembled deepwater operations. A summary of the field test parameters and results is shown in Table 1.

The first field test was performed on a South Texas well operated by *Conoco*. The slurry was easily blended on location, and was mixed and pumped in the well with no problems. The second field test was performed in the Rocky Mountains in a well operated by the DOE and RMOTC in Wyoming. This well had been previously cemented with foam cement and although there were problems with lost circulation, the well required high-strength cement and good zone isolation. One hundred barrels of the ultra-lightweight cement slurry (using 3M 6K ULHS beads) were mixed and pumped with no problems, and the ULHS beads showed no breakage after one hour of conditioning at the surface. Ultrasonic logs performed on the well after the cement operation showed excellent application of the slurry, good bond properties, and good perforating qualities (Figure 3).

Next Steps

With the field-testing phase of the project complete, the next phase of the project includes transferring this technology to the industry. This phase of the project will be accomplished by leveraging the technology transfer capabilities of the joint industry partners, by publishing information in various publications, through seminars and training, and through technology transfer meetings. This phase of the project is expected to begin in early 2003.

Future applications for this product include: critical operations requiring the use of lightweight cements, wells with formation damage occurring from treatments with conventional cements, and coal seam wells. Because of its high strength, low permeability and low density, this slurry would provide excellent bonding in deepwater offshore wells, or high temperature, high pressure land-based wells. ■

For additional information about the results of this project, or for information on ultra-lightweight cement systems, contact Fred Sabins, Cementing Solutions, Inc., at 713-957-4210 or by email at f.sabins@cementingsolutions.com. For additional information about this project, visit the "What's New" page at CSI's website: www.cementingsolutions.com.

The Quest for High Temperature MWD and LWD Tools

By John Cohen, P.E.
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John D. Rogers, PhD., P.E.
U.S. DOE/NETL
Eric Malcore and James Estep
Halliburton Sperry-Sun

Efforts to expand the temperature limits of MWD and LWD tools have seen limited success. New approaches may will be necessary if industry is to meet the demand for gas from deep, high temperature reservoirs.

The search for hydrocarbons is heating up. As shallow, convenient reservoirs of oil and gas become depleted, exploration is extending into deeper horizons, and deeper means hotter. In the U.S., deeper gas reservoirs have been found in the Gulf of Mexico's Mobile Bay, other and deepwater areas, in South Texas, the Permian Basin, and Wyoming.

Earlier this year the U.S. Dept. of Energy's National Energy Technology Laboratory (NETL) initiated a program to fund and develop technology relevant to these deep environments. The "Deep Trek" program includes initiatives to develop high temperature sensors and electronics as well as other methods and tools to drill at depths greater than 20,000 feet. These depths generally exhibit temperatures >176ºC (>350ºF) and pressures >10,000 psi. Currently, at temperatures exceeding 175ºC, deviated drilling must be done without the benefit of MWD (Measurement While Drilling) technology. Further complicating the problem, LWD (Logging While Drilling) technology is essentially limited to 150ºC or less. By comparison, the temperature of deep gas reservoirs in south Texas and the Gulf of Mexico approaches 232ºC (450ºF).

Efforts to extend these capabilities however,however have been underway for some time. In the late 1990s, prior to the current Deep Trek program, NETL, *Maurer Engineering Technology Inc., Sperry-Sun,* and *Halliburton Energy Services* recognized the future need for high temperature drilling and geological measurement technology. In 1997, NETL entered into two partnership projects to enhance the capabilities of high-temperature LWD and MWD tools. The LWD project was to extend the capability of tools (from 140ºC to 175ºC with survivability to 200ºC). The MWD project objective was to extend the temperature of the MWD suite of tools from 175ºC (347ºF) to 195ºC (383ºF).

Although a complete suite of MWD tools was not developed and the MWD project has been discontinued, the project did advance the knowledge base with significant lessons learned and provided important direction to additional research for both MWD and LWD tool development. Changes made as a direct result of work performed under these projects have resulted in improved life and a more robust MWD tool at the previous temperature rating of 175ºC, as well as limited use at higher temperatures. The LWD project, currently still active, also benefited from lessons learned in the MWD project. This article presents a brief summary of the MWD work and the lessons learned.

MWD Project Objectives

The overall objective of the two-phase MWD project was to develop a mud-pulse MWD tool that could be used where downhole temperatures are as high as 195ºC (383ºF). Phase I objectives were to: (1) identify components of existing systems that cannot operate at 195ºC; (2) locate high-temperature replacements or develop new designs,; (3) develop a cooling technology to keep components at acceptable operating temperatures; (4) test new designs and components under high temperatures in the laboratory; and (5) assemble two high-temperature MWD prototype tools and test each in at least one low-temperature well to verify total system performance.

The primary objective of Phase II was to test the prototype tools in up to five directional/horizontal wells where the bottom-hole temperatures were 195ºC (or at least 185ºC), to establish system reliability and collect mean-time-between-failure (MTBF) performance data. The project was discontinued before Phase II was initiated.

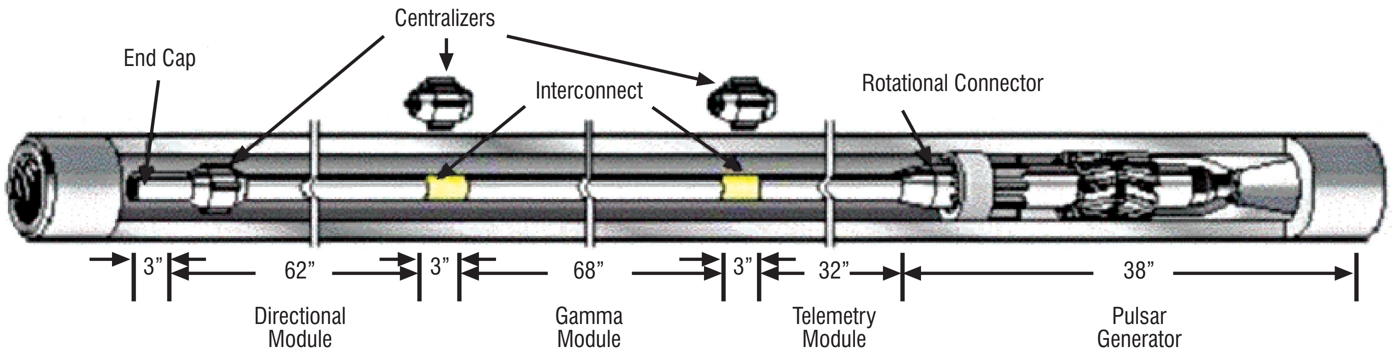

Figure 1: Schematic of MWD Tool

Merger Complicates Effort

The MWD project was co-proposed by *Maurer Technology Inc. (MTI)* and *Halliburton Energy Services (HES)* through its *Halliburton Drilling Systems Division.* During the course of the project, *HES* and *Dresser Industries* merged and Halliburton’s MWD and LWD services became the responsibility of *Sperry Sun,* a former Dresser Industries company. Originally, HES was motivated to participate in the project to improve their standard tool’s high temperature capability. After the merger, Halliburton acquired the *Sperry Sun Solar* 175 MWD tool, which boasted an industry maximum upper operating temperature of 175ºC. After some delay, Halliburton decided to continue with the project, with the goal of upgrading the Solar 175 tool for operations at 195ºC.

After the merger, some of the work accomplished by HES became superfluous (e.g., development of a high-temperature gamma detector based on Geiger Muller tubes was ended since Sperry Sun already had that type of detector). Overall project work continued however, and at the end of the project, *Sperry Sun* had constructed two prototype MWD tools that were successfully tested in the laboratory at 195ºC and then field tested (Phase I) at temperatures up to 180ºC.

Basic System Description

The high-temperature measurement-while-drilling (MWD) tool (Figure 1) includes five primary modules housed in sealed barrels hung inside a non-magnetic collar located above the drilling assembly. Descriptions of the modules and their functions follow.

***Telemetry Module (TM)* –** The telemetry module communicates with other modules, gathering data from the gamma and directional modules, formatted formatting it for transmission, and storing it. The TM also conditions the electric power from the pulser/generator for use by the other modules.

***Gamma Module (GM)* –** The gamma module measures naturally occurring gamma radiation to determine formation type and transition depths between formations. Geiger Muller tubes are used rather than conventional sensors based on scintillation technology, because they are rugged and able to survive high temperatures. Three stacked banks with four Geiger Mueller tubes each make up the sensor section of the GM.

***Pulser/Generator* –** The pulser module generates electrical power and restricts drilling mud flow to create a pressure pulse that can be detected at the surface. It is always connected to the TM and is unique among the modules in this aspect. The pulser contains turbine blades that are driven by the flowing mud to turn a generator and a small hydraulic pump. The hydraulic pump is used to operate a poppet valve that blocks the flow of mud in the drill string, thereby creating a pressure pulse. The TM controls the pulser operations and encodes data into the pulses that are received and decoded at the surface using a pressure transducer and computer.

***Battery Module (BM)* –** The battery module provides power to the tool when there is no flow of drilling fluid to operate the generator, using high-temperature lithium batteries.

***Directional Module (DM)* –** The directional module uses magnetometers and accelerometers to measure the compass direction of the bottom-hole assembly and the angle of the hole. These data, along with depth, are used to calculate the trajectory of the well.

The DM is usually placed as close as possible to the drill bit.

Project Tasks and Work Completed

Work on many tasks was accomplished both before and after the *Halliburton/Sperry Sun* merger. Each objective is highlighted below.

Identify Components and Design Cooling System – *Halliburton* and *Sperry Sun* were able to identify components or circuit designs that failed as temperatures were increased to 200ºC. For circuit design failures, eliminating components or altering the design addressed the shortcomings. Other failures required that new components be substituted for those that could not meet the temperature requirements.

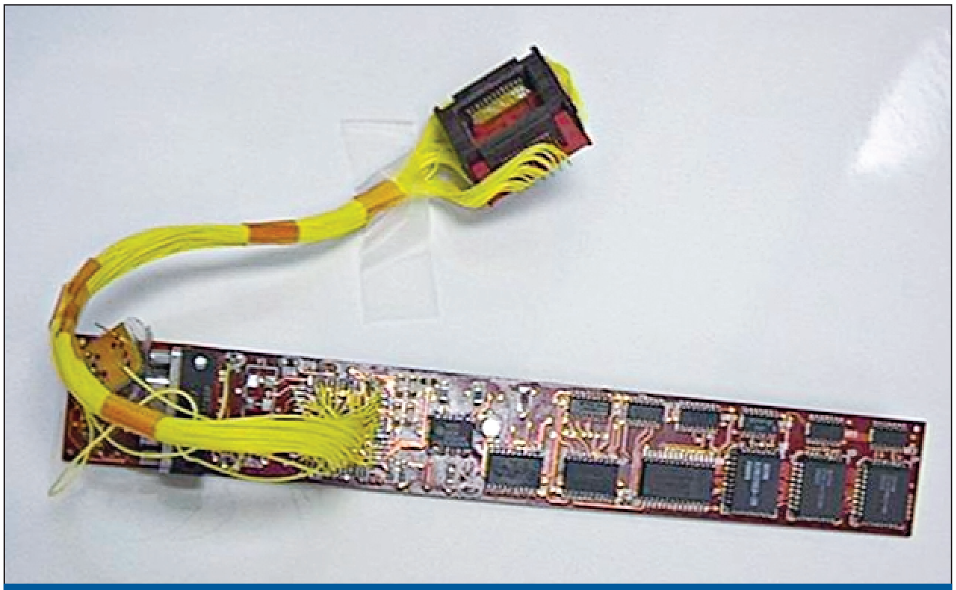

Figure 2: ELCON Hybrid Processing Chip

Halliburton's goal was to identify, test, and use components that were either designed to operate or modified to operate at higher temperatures. *Halliburton* was successful in finding several components that demonstrated improved high-temperature performance, including a hybrid chip manufactured by *ELCON Technology* of Phoenix, Arizona, that was successfully tested at 200ºC for over 700 hours (Figure 2).

Sperry Sun chose to keep the same components (when possible), but identify batches from the manufacturer that functioned at elevated temperatures, believing that increasing temperature capability to 195ºC could be accomplished by locating exceptional batches of components that could survive even higher temperatures.

Halliburton subcontracted with APS Technology of Cromwell, Connecticut to develop an analytical model to simulate cooling of an MWD system and a dummy board, using resistance heating to simulate electrical components. Thermoelectric coolers (TEC) were used to remove heat from within a pressure barrel containing the dummy MWD board. The tests showed that TECs can reduce the temperature inside a pressure barrel and on the circuit boards to acceptable levels, providing a possible solution in the event that high-temperature components are unavailable.

The test data also show, however, that a TEC would consume considerable electrical power, requiring the use of a turbine generator. Power would then only be available when the pumps were operating, so a Dewar-type pressure housing would be needed to insulate the MWD electronics and keep them at below rated temperatures for acceptable periods of time while the pumps were off. Both the generator and housing would increase the cost of this system. In addition, to achieve higher efficiency, the inside of the Dewar would need to be filled with a dielectric fluid, making assembly more difficult.

Design of a High-Temperature Gamma-Ray Detector – The best way to measure gamma radiation at higher temperatures is with *Geiger Muller* tubes. One advantage to the *Halliburton/Sperry Sun* merger was that *Sperry Sun* already had a gamma detector based on *Geiger Muller* tubes. Sperry Sun determined changes needed to upgrade their *Geiger Muller* unit to 195ºC. Testing highlighted problems in the unit's electronics, which were successfully modified.

Selection of High-Temperature Components for Use in MWD/Gamma Tool – Both *Halliburton* and *Sperry Sun* identified components or batches of components that performed adequately at high temperatures. Halliburton, working with Battery Engineering Inc. of Hyde Park, Massachusetts, developed a lithium-/magnesium battery that would operate in the temperature range of 125 – 214ºC. A size DD battery with 25 percent magnesium can be safely used to 200ºC. Current capacity, while reduced to 15 A-hr, is sufficient for at least 250 downhole circulating hours downhole. The primary disadvantage of this recipe is that power output below 100ºC is poor.

Options for overcoming this problem include heaters to maintain the temperature of the lithium/magnesium batteries at minimum operational levels, or a sacrificial nickel-/cadmium battery pack used to power the tool at lower temperatures. The replaceable low-temperature battery pack would shut down and the high-temperature batteries come on-line as the tool's temperature rose above 125ºC.

Sperry Sun had difficulty in proving two directional packages for the test It took testing several packages of magnetometers and accelerometers, before individual magnetometers components could be proven for each of the tool tools, (magnetometers and accelerometers) for the test, the final individual components proven. This area remains as a key item requiring additional work.

Design, Fabricate and Test High-Temperature MWD/Gamma Tool – Both Halliburton and Sperry Sun took advantage of the opportunity presented by the project to make changes in the design of their MWD tools. Sperry Sun enhanced many areas of their tool (Table 1), using their current system as a base and modifying or substituting parts that qualified for higher-temperature service. The final prototype tools were tested in an oven at 193ºC.

A field test was conducted with the two prototype tools at elevated temperatures (180ºC) in Lavaca County, Texas in August 2001. While not the tool's design limit, this temperature range still represented an ambitious test. The tools were used to provide directional services on a sidetrack of a straight hole designed to intersect the formation up-dip above a gas/water contact. Conventional Solar 175 tools were used in the beginning of the operation and the first prototype 195ºC tool was run at 16,500 ft with the first recorded temperature at 178ºC. The tool stopped pulsing after operating on bottom for 59 hours. Data downloaded at the surface at the end of the test showed that the tool had continued to record data for an additional 27 hours. The second prototype tool was then run into the well. Total time for the second tool before data transmission was lost was 26 hours.

Each of the tools was given a post-mortem examination. The first was found to have a failed pulser resulting from failed seals. Data from the tool's telemetry module were successfully downloaded after the operation, demonstrating that the electronics had not failed. Battery voltage was very low (which could have been caused by exposure to high temperatures).

With the second tool, the pulser was also found to have failed, this time due to a bearing that had been inadvertently left out during assembly. It was also determined that the back-up battery in the telemetry module had vented, damaging wiring and electronic components. It was not apparent why the battery had vented. Heat could have been a factor, although these batteries should have been capable of operations up to 214ºC.

Economic Analysis

Preliminary analysis of the economics of the 195ºC tool highlights the greatest obstacle to future commercialization. Costs to screen individual components, then subassemblies, and finally completed tools for high-temperature operations are very high. Tests to date also show a relatively short life for high-temperature tools – on the order of 300 hours (as compared to approximately 1000 hours for a commercial MWD tool operating at temperatures up to 150ºC). Together, these factors mean that the daily cost of the 195ºC tool will be about $14,750 versus $3000 to $4000 for a conventional tool. In addition, high-temperature MWD tools are difficult to prepare, trouble-shoot, and maintain on a continuing basis. It is difficult to predict whether operational experience could increase operational life and reduce manufacturing and maintenance costs, and thereby reduce the daily rate.

Results of the MWD development effort showed that, while it is possible to build a mud-pulse MWD tool that can operate at 195ºC, performance is not yet sufficient for commercial success. The current temperature limit of 175ºC is apparently the practical limit for conventional electronics. This conclusion is further supported by Sperry Sun's decision to market two tools, one for service up to 150ºC and another (the Solar 175) tool for service from 150 to 175ºC. Currently, the bulk of commercial MWD work is at temperatures below 150ºC.

However, industry's perception of future MWD/LWD requirements appears to be changing. Market studies indicate that deeper, higher temperature gas wells are the trend. The DOE can help bridge the gap in perception by presenting data and funding projects that help determine how much gas is located in high-temperature reservoirs. These data may then serve to encourage the MWD industry to place resources into the development of tools for high-temperature operations.

New Platform May Be Required

Increasing the operating temperature (>175ºC) of current MWD (and LWD) tools may require development of a new platform for the electronics used in these tools. This technology already exists in a limited number of components and has been used to develop some special geothermal tools. Sandia National Laboratory has taken the lead role in this area and is developing or interested in the development of tools based on silicon-on-insulator (SOI) technology to overcome high geothermal temperatures.

SOI electronic components have been demonstrated at temperatures of up to 250ºC for hundreds to thousands of hours. Oilfield systems could make use of SOI technology to develop a next generation of tools that could allow raising the current temperature limit (175ºC) to as high as 300ºC. Two other major design changes for high-temperature applications are ceramic packaging and gold wire bonding.

There are several barriers to the development of SOI tools for the oil and gas industry. First, programming would have to be extensively modified. Completely new circuits would have to be developed to use the SOI chips now available. In addition, some components still need to be improved for high-temperature use including magnetometers and accelerometers needed used for determining direction and trajectory of the well. This project has advanced the development of these components, but more work is needed, including the examination of other non-conventional technologies to measure primary MWD parameters, angle, and direction. Perhaps one of the most challenging obstacles to the development of the next generation of MWD tools is the (understandable) reluctance of companies to render obsolete their current inventories of tools.

LWD Tool Development Underway

The LWD project is still underway to develop a 175ºC tool to include directional (geometric position), natural gamma ray, resistivity, Stabilized stabilized Litho litho Density density (SLD), compensated thermal neutron (CTN) porosity, and a pulser to send the reduced formation evaluation data back to the surface by way of pressure pulses in the drilling fluid. Much of the knowledge learned for the LWD project was gained in developing the higher-temperature MWD project.

The LWD tool is 4 ¾ inches in diameter and the entire tool string is approximately 100 feet in length. A 4 ¾ inch Solar (175ºC) SLD measurement tool is in the process of being built and will be rigorously tested at Halliburton's North Belt manufacturing facility before being integrated with the remaining components of the tool in February 2003 for further field testing.

Field- testing has been accomplished on five of the tool components in the North Sea at depths in excess of 15,000 feet MD and temperatures up to 186ºC with excellent success. Field tests have been run in Oman (174ºC), Saudi Arabia (162ºC), and the Gulf of Mexico (154ºC). With the addition of the SLD tool currently under development, testing of the integrated tool string will begin in February or March of 2003 and continue for several months.

Next Steps

DOE leadership and partnership with industry can play a significant role in encouraging the development of high-temperature tools to prepare for the future. The DOE can provide funding to help reduce the risk and offset the loss due to obsolescence of current inventories. ■

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Downhole Fluid Mixing: A Novel Approach for Lowering Stimulation Pressures

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and Gary Covatch
U.S. DOE/NETL

Mixing fracturing fluids downhole, using liquid carbon dioxide and a suite of pump rate and pressure functions, may result in better control of the hydraulic fracturing process and significant cost and safety benefits.

Pumping fracture treatments at high pressures is expensive and can be a safety hazard, particularly in wells with older tubulars in mature fields. For both these reasons, stripper wells are often rejected as candidates for high pressure fracturing stimulation treatments that could result in improved oil or gas recovery. A DOE-supported project has shown that mixing fracture fluids at the bottom of the well, rather than on the surface, may lead to a safer process with lower pumping pressures and lower costs. A second benefit of this approach is an increased ability to alter the treatment mixture at the perforations during the treatment (in real-time), thus facilitating more precise control and fewer out-of-zone fractures.

Stimulation Problems Related to Surface Mixing

Fracture stimulation problems may arise when the pressures required to pump gelled, thickened fluids reach an excessive limit, requiring the operator to prematurely terminate the treatment to avoid rupture of surface equipment or wellbore tubulars. Excessive treating pressures may also occur abruptly during the stimulation fracturing process as a result of premature screenout (if the rate of stimulation fluid bleedoff into the reservoir formation exceeds the rate at which fluid is pumped down the wellbore, causing the proppant to compact within the fracture and wellbore). The operator may elect to reduce the proppant quantity, density, or concentration per volume of fluid, in order to prevent a screenout, however when the reduction is made at the surface, a significant amount of time passes before the altered proppant concentration reaches the formation.

A second problem can arise with the timing of inhibitors. With surface-blended composite fracturing fluids, chemical inhibitors may be mixed into the fluids at the surface to time-delay activation of cross-linked polymer gels. Highly viscous gels are desirable for effective transport of proppant, however, if gelling occurs in the tanks and flowlines before the fluid is pumped, the efficiency of the stimulation job may be compromised due to higher pressures and lower pump rates. If gelling occurs too early or too late, either premature screenout or poor proppant transport can result. Premature gelling creates the potential for exceeding casing or tubing burst pressure. In a 12,000 feet well, for instance, surface wellhead treating pressures often exceed 10,000 psi, and bottomhole treating pressures at depth are significantly higher. High bottomhole treating pressures may crush proppants in the fracture, creating fines, accelerating fracture closure and causing formation damage.

Higher treating pressures also lower pump rates, reducing the amount of fracturing fluid and proppant that can be pumped, increasing horsepower requirements and increasing cost.

Downhole Mixing

This dual-fluid stimulation process, currently under development and final field-testing by *RealTimeZone Inc.* (RTZ), of Roswell, NM, *Halliburton Energy Services (HES)* and the *National Energy Technology Laboratory (NETL)*, involves mixing of separate fluid types downhole to create a composite fracturing fluid at the formation. Downhole-mixing is accomplished by dual injection of different fluids for admixture next to the perforated interval, via coiled or conventional tubing and the tubing-casing annulus. Downhole rheologic properties and proppant concentrations may be modified "on the fly" by adjusting surface pressures and rates.

Downhole-mixing can also be used to create different fracturing fluid phases and thereby induce realtime viscosity

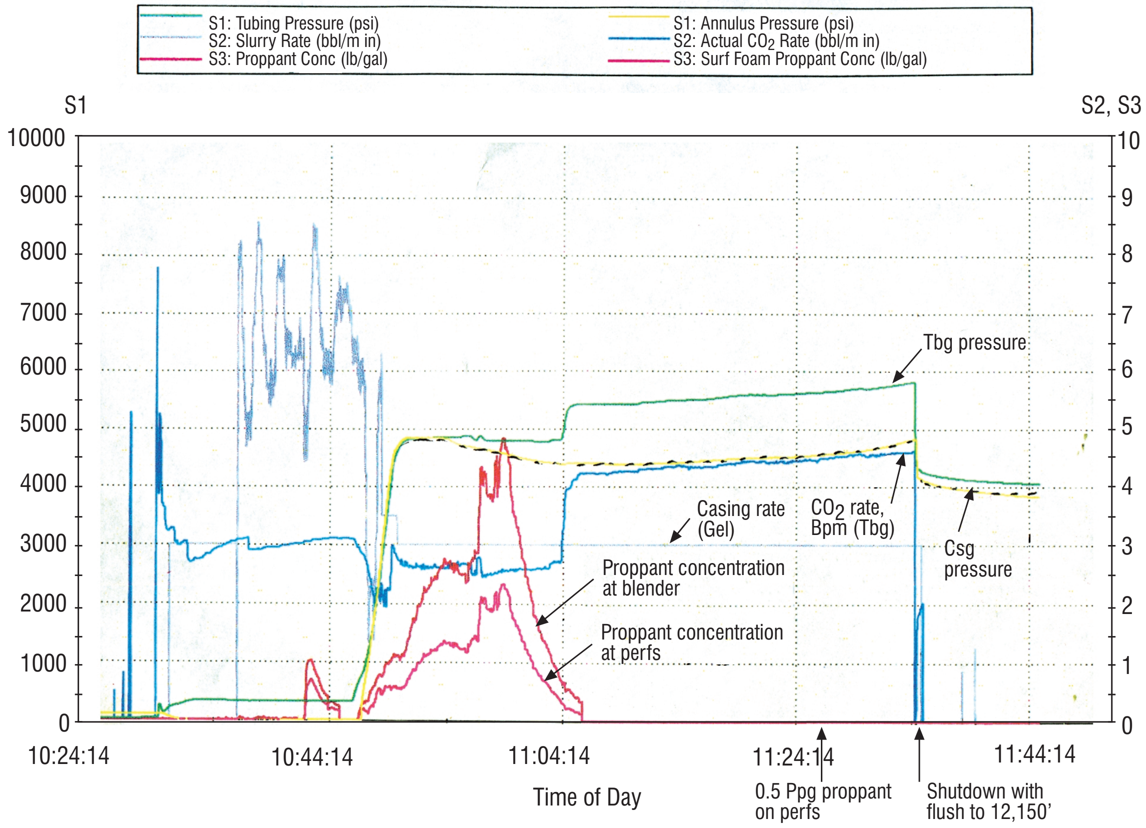

Figure 1: Pressure and Rate Data for Downhole Mixing Fracture Job on Morrow Gas Well

interfingering in the reservoir fracture or fractures, focusing proppant placement and facilitating control of proppant concentrations. The methodology may be combined with real-time fracture monitoring to enable an operator to change fracture propagation and improve resultant fracture geometries, and proppant concentration and placement.

How It Works

During a typical fracturing treatment sequence, fracturing fluid is surface-mixed and pumped in pre-pad, pad, proppant, and flush stages. The fluids, which might also include gelled hydrocarbons, are pumped down the casing while the tubing is a "dead string" that provides the operator with a means of monitoring bottomhole treating pressure during the fracturing process. Alternately, surface-mixed composite fracturing fluid may be pumped down the tubing or pumped simultaneously down both tubing and casing.

With downhole mixing, aqueous gel with nitrogen and proppant is pumped down casing and liquid CO_2 is pumped concurrently down tubing, at constant or variable ratios during successive treatment stages. Downhole-mixing forms a composite fracturing fluid above or adjacent to perforations. Pump rates are varied for the purpose of achieving desirable fracture growth and proppant placement within the reservoir zone. In addition, fluid rheology may be selectively altered, in real-time, as a result of modification of relative pump rates at the surface of tubing and casing.

The net composition of the composite fracturing fluid is variable as a function of the rates that the tubing and casing components are pumped. For example, the composite fracturing fluid may be adjusted, in real-time, from a ratio of 40 percent CO_2-30 percent N_2-30 percent aqueous fluid slurry (with proppant) to a 80 percent CO_2- 15 percent N_2-15 percent aqueous fluid slurry by increasing the volumetric rate of CO_2 pumped down tubing. In addition, the rate of change may be further accentuated by simultaneously decreasing the casing annular pump rate while increasing the tubing pump rate, such as might be indicated by premature screenout and the need to radically reduce proppant entry into the formation. A key element of this methodology is the suite of algorithms and calculation procedures that have been developed and tested to accomplish these changes downhole with confidence.

Potential Benefits

This approach avoids the requirements of high pumping horsepower typically required due to the relatively high friction pressures characteristic of viscous, surface-mixed stimulation fluids. Downhole mixing also has applications in situations where chemical activation at the point of wellbore contact is desirable. For example, precision blending of sodium silicate polymers and chemical activators can be carried out to induce plugging of water-productive zones.

Another potential application would be downhole-blending of nitrogen and methanol-gel to create a fluid comparable in efficiency and proppant transport capability to a conventional nitrogen-foam treatment that is mixed at surface yet exhibits less fluid-pipe friction, resulting in lower pressures and reduced cost.

By providing separate conduits for respective separate fluid compositions at the surface, composite downhole fracturing fluid combinations that might otherwise have been impractical if mixed at the surface, may be permissible. For example, cross-linking may be performed downhole in the casing without relying on “delayed” cross-linking techniques that result from less predictable fluid pH changes.

Three Successful Field Tests

RTZ used the downhole-mixing technique for the first time last fall in a 12,300-foot Morrow gas well in the Sand Point field of Eddy County, NM. The treatment consisted of a methanol gel with 7,000 pounds of bauxite proppant pumped down the annulus and 40 tons of liquid CO_2 pumped down the tubing. The treatment chart shown in Figure 1 illustrates the pumping pressures of tubing and casing during the treatment.

Tubing pressure never exceeded 6000 psi, and the casing side was never above 5000 psi. If the job had been pumped in the conventional manner, the pressures would have averaged closer to 10,000 psi. Liquid CO_2 was used because after the proppant has been placed in the reservoir fracture, the drop in bottomhole treating pressure turns the CO_2 from liquid to gas, allowing the fracturing fluid to be produced back from the formation at a faster rate. Originally scheduled for abandonment, the Sand Point well’s post-fracture production was 200-250 Mcfd. A post-fracture tracer log showed the treatment had been placed in the zone as designed.

RealTimeZone can also combine this downhole mixing methodology with a downhole, real-time, surface readout fracture monitoring system to give an even more accurate picture of where the fracturing fluids are going. Working with HES to incorporate their gamma-ray Spectrascan™ log, RTZ performed a treatment in another Eddy Co., NM well completed in the Willow Lake Delaware oil reservoir. Spectrascan utilizes distinctive radioactive tags on both proppant and fluid to reveal the relative distribution of pumped material within the reservoir fracture.

The Willow Lake well was considered to be a dry hole. The Delaware sandstone showed about 40 to 50 ft of net pay at about 5000 ft depth, with a wet zone 40 to 50 ft thick directly below the pay and no stratigraphic barriers. Most wells in the area produce at 60 to 90 percent water cut because hydraulic fractures invariably grow out-of-zone. Tracer logs have revealed hydraulic fracture heights of 100 to 200+ ft in most wells in this field. RTZ pumped gelled lease oil and proppant down the tubing while pumping CO_2 down the annulus, carefully controlling rates to achieve the appropriate mixing at the perforations. The result was an economic well; 8-10 BOPD at only 20 percent water cut.

A third test well completed this spring was an acid-CO_2 treatment pumped to a Wolfcamp reservoir at 10,500 ft, also in the Permian Basin of New Mexico. By pumping the acid down the tubing and the CO_2 down the annulus, treating pressures could be maintained around 5800 psi, rather than 9000 to 10,000 psi. This test was completed using only two acid trucks and was also successful. The well is producing gas and light oil with a 2200 psi BHP.

Next Steps

The Energy Department’s National Energy Technology Laboratory (NETL) began working with *RealTimeZone* on the development of this methodology in early 1999. The project is now in the final phases of field testing and *Halliburton Energy Services* has licensed the process. With further testing, downhole mixing of fracturing fluids could find increased application in a variety of treatments. When a job can be pumped with less pressure, less horsepower, and less fuel, it opens up opportunities for older wells with older tubing and lower incremental reserves to be stimulated economically. ■

For more information about this process contact George Scott at glsrtz@aol.com or at 505-622-6713, or Gary Covatch at National Energy Technology Laboratory’s Strategic Center for Natural Gas, at 304-285-4589, or via e-mail at gcovat@netl.doe.gov.

Creating a Roadmap for Unconventional Gas R&D

By Tom Engler
New Mexico Tech
and Kent Perry
GTI

Production from unconventional gas resources has grown rapidly over the past decade. What new technologies will be needed to reach even greater levels of production by 2010?

With projections forecasting US natural gas demand reaching 30 Tcf by 2015, experts have pointed to the need to increase our national ability to tap unconventional sources of natural gas: coalbed methane, tight gas sands and gas shales. R&D efforts conducted by Gas Technology Institute (GTI) and others during the past two decades have supported an impressive increase in unconventional gas production from 1 trillion cubic feet (Tcf) per year in the early 1980s to 4 Tcf per year today. The current challenge facing the industry is how to double that total to 8 Tcf over the next 10 to 15 years.

R&D is a particularly important part of this issue because unconventional gas resources are very dependent on new technology to enable production at market-clearing prices. Every year, the average well depth increases, new types of low-permeability formations are explored, and reservoirs become smaller in size. All of these factors combine to make new technology requirements a key strategic component in the future production of unconventional gas.

To help meet this challenge, GTI and New Mexico Tech (NMT) are collaborating to produce a detailed technology plan to help guide the development of unconventional onshore gas resources in the United States. The project specifically calls for a "roadmap" to be developed by the end of 2002 to serve as a guide for technology research programs. As part of this effort, NMT has held a series of focus groups to generate feedback from gas producers - both majors and independents - throughout the United States, as well as from government agencies, National Laboratories, and industry associations. The preliminary results of these sessions are highlighted here.

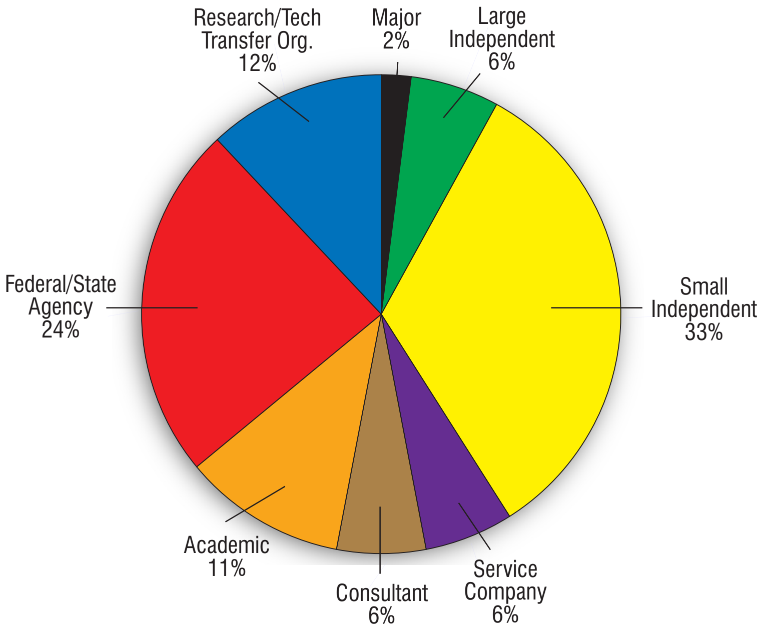

Figure 1: Organizations Represented by Workshop Attendees

Regional Workshops Generate Feedback

A series of five regional workshops were held during the summer of 2002 to help establish recommendations for defining specific short and long-term R&D needs in exploration for and production of unconventional gas resources in the United States. The locations of Farmington, New Mexico; Midland, Texas; Oklahoma City, Oklahoma; Morgantown, West Virginia; and Denver, Colorado were selected for these workshops as representative of the major unconventional gas basins of the country. Invited participants represented a wide range of backgrounds, from producers and service companies to academia to federal and state government agencies. The actual participants reflected these categories (Figure 1). An average of about 25 participants took part in each of the five workshops (127 total participants).

An open discussion format promoted active participation from the attendees. The sessions were organized in terms of plays: low-permeability sands, gas from coal seams, shale gas, and in some cases, deep gas. For each play, the groups ranked the discussed technological needs in order of importance. The highest ranking technological needs from each play were combined and ranked into a final prioritized summary of research needs for unconventional gas.

Preliminary results indicate that feedback on technology R&D needs received at all five workshops fell into three general categories: (1) improved reservoir characterization technologies, (2) improved stimulation/completion technologies, and (3) improved well performance enhancement technologies. The following includes a summation of the views and opinions expressed by participants in the regional road-mapping focus group meetings.

San Juan Basin Meeting

The San Juan Basin focus group meeting was held in Farmington, New Mexico on June 19th, 2002. The discussions were divided according to the four main unconventional plays within the basin: coalbed methane, shale gas, tight gas sands, and deep (pre-Cretaceous) plays. The discussions resulted in the following prioritized list of topics for future R&D.

Handling, treating and disposal of produced water (highest priority) – Novel and inexpensive techniques are needed to reduce the amount of water to be lifted and disposed, or to improve water quality so that it can be used for beneficial purposes at the surface. Downhole separation and water control methods were discussed; however the participants agreed that the best solution would be to produce the water for beneficial use if an inexpensive technology to treat it can be developed. The potential impact of such a technology on meeting future gas demand is large, including: extension of economic well life, lower operating costs, availability of capital to invest in other projects, and the ability to drill new coal bed methane wells that would otherwise be uneconomic because of water disposal costs.

Reservoir characterization using existing wellbores – With targets more elusive, better reservoir descriptions are needed. Emphasis was placed on using existing wellbores, and improving/applying cased hole techniques to better identify bypassed pay zones in existing cased wellbores. Specific goals brought forth by industry include techniques to properly determine gas-in-place volumes within unconventional reservoirs, identification of pay in thinly-laminated shale gas reservoirs, and more precise identification of natural fractures and their orientation in tight gas sands and coalbeds.

Stimulation – The unpredictability of hydraulic fracture response in coalbed methane wells leads to a need for diagnostics to improve the understanding of CBM well completions. Proper application of appropriate fracture fluids in coalbeds, shales and tight-gas sands was also identified as a concern and subsequent need.

Advanced drilling technologies – Previous results of horizontal wells in CBM outside of the major Fruitland fairway were dismal, but the reasons for this poor performance are unclear. Possible causes include: (1) a poor understanding of stress states of the coals and a consequent lack of ability in predicting response to stimulation; (2) inappropriate or non-optimal drilling techniques; (3) poor understanding of natural fracture orientation; and (4) poor understanding of the detailed depositional environments and stratigraphic variability of the coal. Participants in the workshop identified the following two primary technology development needs: techniques for underbalanced horizontal and/or multilateral drilling, and techniques for lower cost drilling of horizontal wells (e.g. coiled-tubing drilling, etc.) that are competitive with hydraulically fractured vertical wells for CBM and tight-gas sand reservoirs.

Several common themes that recurred throughout the Farmington discussions were the importance of utilization of existing wellbores, the need to find ways to extend the life of marginal wells, and an emphasis on the need to focus on field development versus exploration technologies.

Permian Basin Meeting

The Permian Basin focus group meeting was held in Midland, Texas on June 27th, 2002. A balanced representation among majors, independents and service companies was achieved, resulting in alternative viewpoints to challenging problems. The four current and potential plays in the Permian Basin are identified as: low-permeability gas-bearing cherty carbonates; low-permeability gas-bearing sands; shale gas; and coalbed methane. A majority of the discussion involved low-permeability carbonates and sands. Coalbed methane is a minor target and thus had limited discussion and response. Shale gas is particularly important (e.g., the Barnett Shale in the Fort Worth Basin) and was also actively discussed at the meeting.

A common concern was the lack of, or need for, access to data and the acquisition of data. This concern was repeated for several plays, and was evident in the priority list generated. The discussions resulted in the following prioritized list of topics for future R&D.

Stimulation (highest priority) – Technology needs exist in developing effective stimulation techniques in low-permeability carbonates and sands. The carbonate reservoirs are composed of a mixture of limestone and chert, and are typically completed with horizontal wells. In this case, novel techniques for acidizing and acid-fracturing these wells are needed. Criteria for stimulation candidate selection were also identified as a priority. Technology needs identified in low-permeability sands include developing the ability to better determine formation damage due to fracturing fluids and to investigate cleaner and more efficient fluids and proppants.

Play-based resource assessment – There is a need to better characterize unconventional opportunities in the Permian Basin through the development of comprehensive, detailed, play-based analysis. Specifically, there is a need to identify and delineate new plays that have been overlooked and identify the larger targets within these areas. Recommendations included fracture studies (micro- to macroscale); regional play analyses that integrate geologic, geophysical and engineering data, and a resource assessment of shales in the Permian Basin. Also, there is a need to compile and aggregate information already available.

Completion strategies in horizontal wells – Low-permeability carbonates are typically completed with a horizontal section with or without laterals. Several key unanswered questions involve determining the best practices for completions, and the optimal number, length and orientation of laterals.

Expert systems – As an extension to the item above, several participants expressed the need for development of a decision-making methodology for designing vertical, horizontal and horizontal-plus-lateral wells. The need identified was the development of a set of criteria regarding drilling, completion, stimulation, and related processes to aid in deciding the appropriate well type and completion for a given target.

Reservoir imaging – Improvements in tomography, shear wave seismic, and borehole imaging are needed to improve reservoir description capabilities.

Gas processing for low-BTU gas – Abundant low-BTU gas with concentrations of non-hydrocarbons (e.g., CO_2, N_2, H_2S) creates the need for improved gas processing techniques to separate non-hydrocarbon gases from hydrocarbon gases, thereby enhancing the heating value of the gases and making them usable and marketable. One possible solution identified as worthy of research was re-injection of such gas into a depleted oil zone, with the possible result of simultaneously sweetening the gas and increasing oil recovery from the depleted oil zone in the process.

Removal of liquids from deep gas wells – Liquids in deep gas wells pose a serious problem and a need exists to develop a lifting system to efficiently unload such wells and flow gas. This technology can also can be extended to horizontal sections and laterals.

Oklahoma City Meeting

The Oklahoma City focus group meeting was held on July 31st. A total of 42 participants attended the meeting. A number of ideas for each type of unconventional resource were discussed; however, the final list of identified R&D needs included the following. The group considered all four of the categories listed to be of equal importance, and therefore no single category was given higher priority than the other.

Data mining – Across all plays there is a need for data acquisition and analysis, as well as the broad dissemination of such data and data analyses.

Completion practices/stimulation – Understanding rock/fluid interactions and fluid compatibility problems for low-k sands, shales and coals was identified as an area where additional R&D is needed. A need for post-stimulation diagnostics and improved fracture models for unconventional gas reservoirs was also highlighted. Development of a "best completion practices" methodology for coal seams was identified as a need, due to the variety of completion methods that have been attempted in this basin, with variable degrees of success.

Reservoir characterization – Development of better pay identification techniques was identified as a particular need. Improved techniques are needed for thin beds (such as in shale gas), as well as in the complex structure-stratigraphy-depositional environment of low-k sands and carbonates. Discussion centered on the need for improvements in seismic, log and log interpretation models, geochemistry and core analysis.

Producibility models – Beyond gathering data, the next step is to appropriately apply modern technology to the understanding and identification of unconventional gas reservoirs.

Other general observations from this meeting included the perception that drilling-related R&D needs (for shallow targets) were not an issue, and that in general, horizontal and/or multilateral wells were cost-prohibitive and not extraordinarily successful. Also, deep gas (+17,500 ft) potential was a topic unique to this meeting. There was an expression of interest in the development of technologies focused on exploration and development of this resource.

West Virginia Meeting

A total of 19 participants attended the August 5th, West Virginia focus group meeting. Four states (PA, WV, KY, OH) were well represented by the unconventional gas experts from their geological surveys, with expertise from the entire group extending from NY through VA. In this region, the “technology end users” are for the most part small independents and utility companies, without the time or means to carry out research, faced with the task of maintaining production from mature reservoirs where operating-cost management is critical. Therefore, a common theme in all discussions was the need for technology to develop cost-effective solutions to problems.

Sessions included discussions on shale gas, gas from coal seams, and low-permeability gas sands/carbonates. Major issues from each play were discussed and individually ranked, and the results were compiled into a list of the top six identified needs, the top four of which were considered to have equal priority.

Reservoir characterization – An identified need was improvement in the understanding of reservoir architecture in sands and carbonates, as well as coal quality characterization. In all reservoir types there is a particular need for an improved ability to characterize natural fractures or cleats.

Need for coal gas desorption data – The need for better data acquisition and analysis technologies prevailed throughout all of the plays, but there is a specific need for coal gas desorption data to support play-based studies.

Extending well life – The last general theme was related to enhancing production performance and thus extending the life of wells. This could be accomplished through improved stimulation techniques or artificial lift methods.

Play-based studies – The need for regional play-based studies that can be made available to the industry was also identified. The collection, compilation and analysis of existing but dispersed data is a valuable benefit to organizations without the resources to carry out this type of activity.

Core drilling/evaluation program – Similarly, the collection of data through coring and formation evaluation programs was seen as an important way to provide a base level of data for improved decision-making in a cost environment that often precludes such data acquisition at the individual company level.

Multilaterals/reduce well costs – There is a need for R&D on technologies to reduce the cost of drilling and improve the success of multilaterals in this basin.

Rocky Mountain (Denver) Focus Group Meeting

The Rocky Mountain focus group meeting was held on August 15th, 2002 at the GTI/IPAMS office in Denver, Colorado. A total of 21 participants with wide-ranging knowledge of unconventional gas resources in the Rocky Mountains were present for the workshop. The majority of the group were producers, with representatives from government agencies and service companies present as well. The highest ranking technological needs were combined into the following prioritized list.

Natural fracture imaging/assessment/prediction (highest priority) – There is a need to better understand how depositional facies and stress state control natural fractures, with the goal of predicting lateral variations in fracture density and fracture trends. This need, originally proposed for low-permeability sands, was also identified as a need for coal seam gas (predicting cleat occurrence and understanding the relationship between cleating and maturity level) as well as shale gas.

Production performance monitoring and evaluation – Typically, wells are completed and stimulated in numerous pay zones, with little understanding by the operator of which zones are contributing to the flow

Table 1: Summary of Unconventional Gas R&D Needs

Topic	San Juan	Permian	Oklahoma	West VA	Rocky Mt.
Reservoir characterization, imaging	●	●	◆	◆	◆
Stimulation	●	◆	◆		
Play-based resource assessment		●		◆	●
Data mining, data collection			◆	◆	
Producibility models			◆		
Handling, treating and disposal of produced water	◆				
Extending well life				◆	
Advanced drilling technologies, drilling cost reduction	●			●	
Completion strategies for horizontal wells		●			
Expert systems		●			
Processing of low-BTU gas		●			
Removal of liquids from deep gas wells		●			
Core drilling/evaluation				●	
Production performance monitoring and evaluation					●

◆ = Top Priority

stream. Continuous, real-time, in-situ monitoring of pressures, production, temperature, and related parameters would help to correct this problem. Development of a system of downhole sensors utilizing current fiber optics technology in the casing (e.g., "smart casing"), was identified as an R&D opportunity to address this need.

Shale gas play assessment – The group recognized the potential for shale gas in the basin, but identified a general lack of understanding of shale gas problems and technology needs across the basin. For this reason, the third priority was the need for a play-based assessment of Rocky Mountain shale gas potential and technology issues.

Areas of Consensus Identified

Although a wide spectrum of topics were discussed, there was some consensus across the regions in assigning a high priority to reservoir characterization, stimulation, play-based resource assessments, and data collection (Table 1). Technology needs for reservoir characterization were led by the need for improved methods and interpretive models for delineation, identification, and quantification of natural fracture systems. Under stimulation, the emphasis was on R&D to improve fracture diagnostics, develop less-damaging fracture fluids, and modify applicable fracture models for unconventional gas reservoirs. Also important were improved methods/tools for net pay determination and play-based geologic studies. A final issue was the need for collecting, warehousing and sharing data, from geochemical and petrophysical data to fracture treatment reports to play-based studies and assessments.

Several unique regional needs were also identified. For example, in low-permeability carbonates in the Permian Basin the need for improved completion strategies and stimulation techniques for horizontal and multilateral completions were identified as having the potential to make a significant impact on gas recovery. Another example is the need for appropriate technologies for exploration and development of deep gas (+17,500 ft) targets in the mid-continent region.

Overall, the process was successful in providing important industry input into the development of a roadmap for future unconventional gas research and development. ■

For more information on the results of this effort and the preparation of the R&D roadmap, contact the authors. Tom Engler, New Mexico Institute of Mining and Technology, can be reached at engler@nmt.edu or at 505-835-5207. Kent Perry, Director, Exploration, Production & Gas Processing at GTI, can be reached at kent.perry@gastechnology.org or at 847-768-0961.

Thermoacoustics for Liquefaction of Natural Gas

By Greg Swift
Los Alamos National Laboratory
and John Wollan
Praxair

A prototype device for liquefying natural gas using thermoacoustics is capable of producing 500 gallons per day of LNG, consuming 35 percent of the incoming gas in the process. Larger capacities operating at higher efficiencies are on the drawing board.

One ordinarily thinks of a sound wave as consisting only of coupled pressure and position oscillations. In fact, temperature oscillations accompany the pressure oscillations and when there are spatial gradients in the temperature oscillations, oscillating heat flow occurs. The combination of these oscillations produces a rich variety of “thermoacoustic” effects. In everyday life, the thermal effects of sound are too small to be easily noticed; for example, the amplitude of the temperature oscillation in conversational levels of sound is only about 0.0001°C. However, in an extremely intense sound wave in a pressurized gas, these thermoacoustic effects can be harnessed to create powerful heat engines and refrigerators. Whereas typical engines and refrigerators rely on crankshaft-coupled pistons or rotating turbines, thermoacoustic engines and refrigerators have no moving parts (or at most only flexing parts without the need for sliding seals). This simplicity, coupled with reliability and relatively low cost, has highlighted the potential of thermoacoustic devices for practical use. As a result, thermoacoustics is maturing quickly from a topic of basic scientific research through the stages of applied research and on to important practical applications.

In this article, we introduce the basic principles of thermoacoustics and describe progress toward their use for liquefaction of natural gas. Thermoacoustic natural-gas liquefiers are surprisingly simple: They use no exotic materials, require no close tolerances, and are little more than welded pipe and heat exchangers filled with pressurized helium. This simplicity, along with the reliability and low maintenance inherent in thermoacoustic technology, suggests that thermoacoustic liquefiers could enable economic recovery of marginal gas resources such as associated gas from offshore oil wells, gas accumulations at remote locations, and even the recovery of landfill gas and marginal coal seam gas accumulations. In addition, the technology could find an application in areas where smaller-scale gas liquefaction is needed: liquefaction at seasonal peak shaving facilities and at fleet-vehicle fueling stations.

Thermoacoustic Basics

Many varieties of heat-driven thermoacoustic refrigeration systems exist, but in this article we consider only a toroidal thermoacoustic-Stirling hybrid engine driving a thermoacoustic orifice pulse tube refrigerator (Figure 1). Parts (a) and (b) of Figure 1 show the half-wave resonance present in the apparatus illustrated by the schematic in (c), where the engine is at the top and the refrigerator is at the bottom. Heat exchangers (H_X) and a regenerator in the engine convert some of the heat power (Q_H) from burning natural gas at a hot temperature (T_H) into acoustic power (W), rejecting waste heat power (Q_0) to a water stream at ambient temperature (T_0). Acoustic power is consumed by the refrigerator, which uses it to pump heat (Q_C) from a liquefying natural-gas load and rejects waste heat ($Q'_0 + Q''_0$) to the ambient water stream. Each of the heat exchangers may be of finned-tube or shell-and-tube construction, as open to helium flow as possible. Each regenerator usually consists of a pile of stainless-steel screens, supporting the smooth temperature profile between the two adjacent heat exchangers.

Thermodynamically, acoustic power is just as valuable as other forms of “work” such as electric power or rotating-shaft power. The first law of thermodynamics determines that $W+Q_0 = Q_H$ in the engine. The second law shows that the engine efficiency W/Q_H is bounded by the Carnot efficiency, $1 - T_0/T_H$. The most efficient thermoacoustic engine to date has achieved 40 percent of the Carnot efficiency, while the most powerful has produced 17 kW of acoustic power. Similarly, in the refrigerator, the first law of thermodynamics determines that $W + Q_C = Q_0' + Q_0''$; the second law shows that the efficiency Q_C/W, known as the coefficient of performance, is bounded by the Carnot expression $T_C/(T_0 - T_C)$. The most efficient thermoacoustic orifice pulse tube refrigerator to date has achieved 25 percent of this Carnot bound.

One of the most important large dimensions in a thermoacoustic device is the length of its resonator, which (together with the helium sound speed) determines the operating frequency, just as the length of an organ pipe determines its pitch. This length typically ranges from 10 cm for the simplest experimental systems to 10 m for today's most efficient and mature systems. The resonator shown in Figure 1 uses a half-wavelength standing wave, shown schematically in parts (a) and (b) (but without details of the wave within the engine and refrigerator). This wave appears spontaneously whenever the temperature in the engine's hot heat exchanger is high enough, and the amplitude of the wave increases as the heat supplied to the hot heat exchanger increases. In parts (a) and (b), the pressure and position waves are shown at two times: the red curves show these variables when the helium is at the uppermost extreme of its position in the resonator, with density and pressure highest at the top of the resonator and lowest at the bottom, while the blue curves show them 180° later in the cycle.

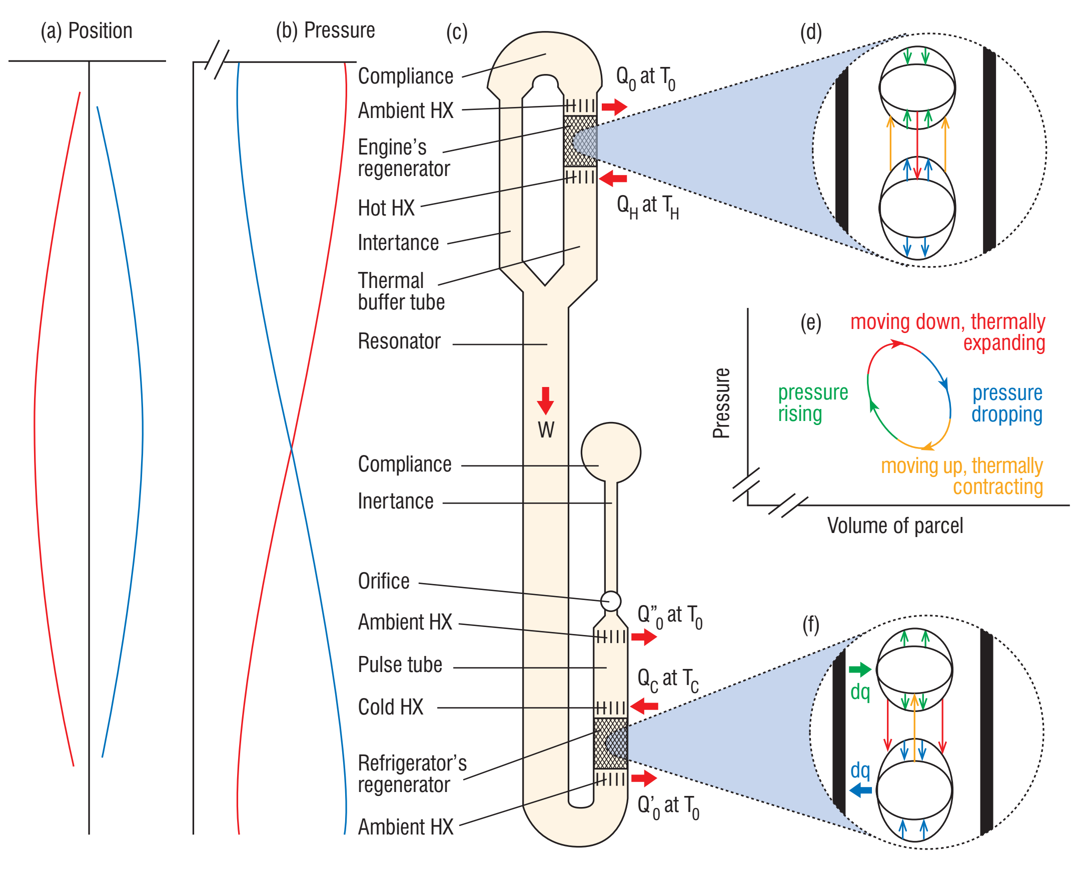

Figure 1: Schematic of a Heat-driven Thermoacoustic Refrigeration System

How the Engine Works

To understand the conversion of heat to acoustic power by this simple engine, consider the magnified view of part of the regenerator shown in Figure 1, part (d), which shows a typical parcel of helium at four instants of time as it oscillates in position, pressure, temperature, and density, exchanging heat with the nearby solid in the regenerator. The tiny pore of the regenerator is shown as a smooth-walled channel for simplicity.

The wave carries the helium up and down along the pore, compressing and expanding it, with time phasing such that it is most pressurized while it is moving down and most depressurized while it is moving up. In typical thermoacoustic engines and refrigerators, the amplitude of the pressure oscillation is 10 percent of the mean pressure, and the amplitude of motion is a similar percentage of the length of the regenerator. Thermal contact between the oscillating helium and the solid wall of the pore, plus the externally imposed temperature gradient, add a new feature to what would otherwise be a simple acoustic oscillation — oscillatory heat transfer between the helium and the solid. While the helium is moving downwards, it encounters ever warmer portions of the regenerator, so it absorbs heat and expands; while the helium is moving upwards, it rejects heat and contracts.

Figure 1, part (e), a pressure-volume

(p–V) diagram for the parcel of helium illustrated in part (d), shows that the helium does net work ($\int p\, dV$) on its surroundings because expansion takes during the high-pressure time of the cycle and the contraction during the low-pressure time. This process depends on the correct time phasing between motion and pressure, which is maintained by inertial and compressive effects in the ductwork near the regenerator. The net work that the helium does on its surroundings is produced at the resonance frequency. Thus, the parcel of helium shown in (d), and all others like it within the regenerator, deliver acoustic power to the wave, while the wave sets the frequency of the power production.

Each parcel of helium also deposits a little heat (not shown in Figure 1) at one location in the regenerator while the pressure is rising and the parcel is relatively stationary near the upper extent of its motion. It absorbs that heat near the lower extreme of its motion, at a warmer location in the regenerator, when the pressure is falling. With respect to heat, all parcels act like members of a bucket brigade, with the overall effect being absorption of heat at the hot heat exchanger and rejection of heat at the ambient heat exchanger.

Pore Size

The pore size in the regenerator determines the nature of the thermal contact between the regenerator solid heat capacity and the moving helium. Good thermal contact is needed to accomplish the cycle shown in Figure 1, because the temperature of the helium should match the local solid temperature while the helium moves. Analysis shows that a spacing between plates of a fraction of a thermal penetration depthd $\delta_K = \sqrt{K/\pi f \rho c_p}$ is best, where K is the thermal conductivity of the helium, ρ is its density, c_p is its isobaric specific heat per unit mass, and f is the frequency of the acoustic oscillation; δ_K is roughly the distance heat can diffuse through the helium during a time $1/\pi f$. In today's thermoacoustic systems, δ_K is typically a fraction of a millimeter. (Pores too tight impose too much viscous drag on the helium.)

How the Refrigerator Works

The basic principle of operation of the thermoacoustic orifice pulse tube refrigerator is very similar to that of the thermoacoustic engine. A magnified view of part of the refrigerator's regenerator in Figure 1, part (f), illustrates one typical parcel of helium as it oscillates in position, pressure, temperature, and density, exchanging heat (dq) with the nearby solid in the regenerator, moving that heat up the temperature gradient. As the helium oscillates along the refrigerator's regenerator, it experiences changes in pressure. At the lower extreme of its motion, the typical parcel of helium rejects heat (dq) to the regenerator, because the pressure rises while the helium is relatively stationary at that location. Similarly, at the upper extreme of its motion, it absorbs heat (dq) from the regenerator, because the pressure rises while it is relatively stationary there. Thus, the parcel of helium moves a little heat along the regenerator, up the temperature gradient, during each cycle of the acoustic wave. All the other parcels in the regenerator behave similarly, so that the overall effect, again like in a bucket brigade, is the net transport of heat from the cold heat exchanger to the ambient heat exchanger.

The helium also consumes acoustic power from the wave (not shown in Figure 1), because the thermal expansion of the helium, attending its downward motion, occurs during the low pressure time of the acoustic wave, and the thermal contraction, attending its upward motion, occurs during the high pressure time. The resulting acoustic power absorbed by the helium is supplied by the thermoacoustic engine, transmitted to the refrigerator through the wave in the resonator.

Development History

Heat driven acoustic oscillators have been known for over a century — the earliest and simplest was discovered accidentally by European glassblowers. But an accurate theory applicable to thermoacoustic phenomena was not developed until the 1970s, through the efforts of Nicholas Rott and coworkers at ETH-Zurich. Rott's theory is based on a low-amplitude linearization of the Navier-Stokes, continuity, and energy equations, with sinusoidal oscillations of all variables.

In the early 1980s, the thermal-physics team at Los Alamos, supported by BES in DOE's Office of Science, was frustrated by the large number of precision moving parts required for their experiments on the thermodynamic behavior of near-critical liquids in heat engines. While looking for simpler engine designs, they read the publications of Peter Ceperley at George Mason University, who had realized that the timing between pressure changes and motion in Stirling engines is the same as in a traveling sound wave (Ceperley, 1979). Inspired by his insight, the Los Alamos researchers began considering acoustic technology to eliminate moving parts. Eventually, they brought together a thermodynamic point of view, acoustic techniques, explicit heat exchangers, and Rott's theory, producing the first powerful thermoacoustic engines and the first thermoacoustic refrigerators. Fundamental research on

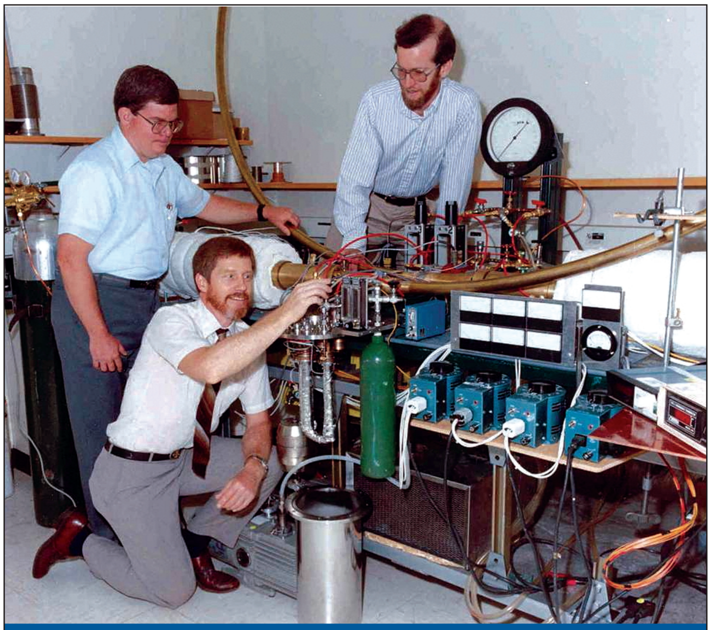

Figure 2: First Thermoacoustically Driven Pulse Tube Refrigerator

Figure 4: First Acoustic Liquefier

thermoacoustics has grown ever since, at Los Alamos and throughout the world.

In the late 1980s, a partnership between the Los Alamos team and Ray Radebaugh at the National Bureau of Standards (now National Institute of Standards and Technology) in Boulder combined a thermoacoustic engine with an orifice pulse tube refrigerator to create the first cryogenic refrigerator with no moving parts (Figure 2). This device was dubbed the "Coolahoop" because the bent brass portion of the half-wavelength acoustic resonator (extending upward in Figure 2) resembled a hulahoop (Radebaugh, *et al.*, 1991). In the photo, the pulse tube refrigerator is the silver-colored "U" at bottom center, while the two thermoacoustic engines are under the bulky white insulation to the right and left of the refrigerator.

Even though this early system had only 5 W of cooling power at 120 Kelvin, Radebaugh believed from the outset that the best application for this heat-driven refrigerator would be liquefaction of natural gas, using combustion of gas as the heat source. A typical modern gas liquefaction plant costs a billion dollars, liquefies 10^4 m^3/day, and has substantial operating and maintenance costs. The need for relatively small, reliable, inexpensive liquefaction equipment seemed clear and an "acoustic liquefier" seemed to fit the need perfectly. The goal of an acoustic liquefier with a capacity of 10,000 gallons per day (gpd) followed, eventually including economic analysis for arrays of such liquefiers on floating LNG production/storage vessels and oil/gas separation vessels (van Wijngaarden, 1999; Figure 3).

Cryenco, a small manufacturing company in Denver, began working on this technology in 1994. The following year, DOE's Office of Fossil Energy (through NETL) began supporting Los Alamos team's partnership with *Cryenco*. Hardware development continued in Denver through many transitions, most recently as Praxair acquired the project. While working on the Denver development, the Los Alamos researchers have continued research on fundamentals, increasing engine efficiency and bringing thermoacoustic improvements to orifice pulse tube refrigerators.

Figure 3: Illustrations of an Acoustic Liquefier and Offshore Applications

Prototype Acoustic Liquefier Hardware

The first natural-gas-fired thermoacoustic liquefier was completed in Denver in 1997 (Figure 4). It achieved a liquefaction capacity of 140 gpd of LNG, producing 2 kW of refrigeration power at –140°C.

The second phase of hardware development, which began in mid 1999, has been the development of an efficient 500 gpd system (Figure 5). The thermoacoustic portion of the system is prominently visible in Figure 5, with the engine on top and refrigerators on the bottom, linked by a half-wave resonator. The natural gas burner is at the very top, under the blue banner. The engine is in the large bulge below the burner. The refrigerators are hidden inside the large, cylindrical vacuum insulation can near the bottom, but two of their slender inertances and compliances are visible above the vacuum can. The thermoacoustic working helium is at an average pressure of 450 psi, with oscillations up to ±45 psi in amplitude at a frequency of 40 Hz.

In this system, three refrigerators are used, driven in parallel by the thermoacoustic wave but connected in series with respect to the natural-gas stream so that the first acts as a natural-gas precooler, the second removes the rest of the sensible heat and some of the latent heat, and the third removes the rest of the latent heat. The design calls for the engine and resonator to deliver 30 kW of acoustic power to the refrigerators, whose combined cooling power is 7 kW. The burner delivers heat to the engine, and is made more efficient by a traditional recuperator to preheat the incoming fresh air by capturing heat from the flue. Waste heat is removed from the engine and the refrigerators by circulating water at ambient temperature. Overall system efficiency should yield liquefaction of 65 percent of a natural-gas stream while burning 35 percent.

Figure 5: Current Protoype 500 GPD Acoustic Liquefier

In 2001, the 500-gpd system was operated at 60 percent of its design pressure amplitude, with the engine producing 12 percent of its design power and each of the three refrigerators running separately at 25 percent of their design powers. All thermoacoustic phenomena were working as expected, but a crack in an inaccessible weld prevented testing at higher powers. During 2002, this system is being rebuilt, including dramatic improvements to the burner and burner-engine heat exchanger. Financial support for this effort is provided by Praxair and NETL.

Next Steps

The next step in capacity will target 10,000 gpd, the largest size that we believe can be factory produced en masse and transported by rail. Initial brainstorming is underway and serious engineering design will begin soon. This effort will be financed by *Praxair* and by the Advanced Technology Program of the National Institute of Standards and Technology.

However, the development of an efficient, low-cost acoustic liquefier is challenging. Even the 500 gpd system is a scaleup of a factor of 1600 in cooling power over the first laboratory demonstration, which used simple electric heat to power the engine and an electric-heat test load on the refrigerator, and had such poor efficiency that it would have liquefied only 9 percent of a natural-gas stream while burning the other 91 percent. Nevertheless, the 10,000 gpd system is expected to liquefy 80 percent of its throughput, and we expect that further improvements can eventually bring the efficiency close to 90 percent without compromising the low cost and reliability of the thermoacoustic approach.

Back to Basics

Readers familiar with Stirling engines or refrigerators will recognize that the processes in the regenerators and heat exchangers discussed above in the context of Figure 1 are identical to the processes in Stirling devices. Hence, another way to view thermoacoustics is as one chapter in the story of the elimination of moving parts and sliding seals from Stirling devices — a story in which earlier chapters include Beale's invention of the free-piston Stirling engine and Gifford and Longsworth's invention of the basic pulse tube refrigerator (Beale, 1969; Gifford and Longsworth, 1965). A key aspect in the thermoacoustics chapter is the deliberate use of inertial effects in the oscillating helium. A moving slug of helium can behave inertially much like a moving solid piston, bouncing against the compressibility of nearby helium to act like a spring-mounted mass. From this point of view, the half-wave resonator of Figure 1 can be thought of as if the mass of the helium in the central third of the resonator bounces resonantly against the compressibilities of the helium in the upper and lower thirds of the resonator, the resulting resonance acting like a flywheel to keep the thermoacoustic engine working from one expansion stroke to the next. The narrow portions of the system labeled "inertance" are also local accentuators of inertial mass, enforcing the correct amplitude and time phasing of the gas motion in the nearby regenerators. Portions labeled "compliance" accentuate compressibility.

Another key aspect of the elimination of moving parts from Stirling systems is the use of pulse tubes and thermal buffer tubes in place of cryogenic or red-hot pistons. These portions of the system maintain thermally stratified adiabatic oscillating flow, thereby transmitting acoustic power from the cryogenic temperature (in a refrigerator) or the red-hot temperature (in an engine) to ambient without suffering from convective heat leak. Some current fundamental research in thermoacoustics is directed toward understanding and maintaining this thermally stratified condition in the presence of violent oscillating flow.

Efficiency and power density are two key figures of merit for any energy-conversion technology. The power of thermoacoustic devices is roughly proportional to $p_{avg}Aa(p_{osc}/p_{avg})^2$, with p_{avg} the average pressure, A the cross sectional area of the regenerator, a the sound speed of the helium, and p_{osc} the amplitude of the oscillating pressure. Helium has the highest sound speed of the inert gases, so high-pressure helium is used in most thermoacoustic systems, including the acoustic liquefier. This leaves p_{osc}/p_{avg} as the primary variable which might be increased in order to increase power per unit area. Unfortunately, increasing p_{osc}/p_{avg} generally reduces efficiency, as a variety of higher loss processes such as turbulence grow in importance, and as the demands on heat exchangers increase. As thermoacoustics matures from scientific inquiry to realistic engineering, these are among the tradeoffs that must be made. ■

For more information contact the authors, Greg Swift, with Los Alamos National Laboratory at swift@lanl.gov or via telephone at 505-665-0640, or John Wollan with Praxair at John_Wollan@praxair.com or by telephone at 303-549-7204. A more complete, animated version of Figure 1 (for PCs, not Macs) can be obtained by downloading TashOpZp.exe from http://www.lanl.gov/thermoacoustics/movies.html. Further background on the fundamentals of thermoacoustics is available at http://www.lanl.gov/thermoacoustics/, which includes links to journal publications and a book. Information about the natural-gas liquefier is also available at http://www.lanl.gov/mst/engine/econ.html.

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New Models Predict Consequences of LNG Releases

By Jerry Havens and Tom Spicer
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Gas Technology Institute

Efforts at the University of Arkansas have resulted in computer models that accurately predict the behavior of high-density methane vapor releases from LNG tanks.

Renewed global interest in LNG as a means of supplying growing gas markets has led to an increase in the number of proposed LNG terminals around the globe. Some of these include options (e.g. several types of offshore terminals) and locations not considered before. At the same time there is a heightened sense of concern over the potential consequences of an LNG leak at such facilities. The need for answers to contingency planning questions concerning possible accident scenarios or terrorist threats will require more specific and thorough consequence assessments. Project developers recognize that the economic burden of increased safety requirements will be considerable, and are eager to employ modeling tools that can provide insight as to the lowest cost options.

In the US, the Code of Federal Regulations (CFR 49 Part 193) prescribes safety standards for LNG facilities subject to federal pipeline safety laws. This Code specifies requirements for thermal radiation protection and flammable vapor-gas dispersion protection, as well as for seismic activity, flooding, soil characteristics, wind forces, severe weather, adjacent activities, and separation between facilities and site boundaries.

Beginning in the late 1970s and early 1980s, Gas Research Institute, now Gas Technology Institute (GTI), sponsored extensive research programs to develop and improve methods to specify the thermal radiation and gas dispersion protection zones at LNG terminals. The Chemical Hazards Research Center at the University of Arkansas (CHRC) remains at the focus of the GRI-GTI research program. This article presents a brief description of the history and current status of CHRC's research on gas dispersion.

Early Model Development

In the mid-seventies and early eighties, in response to public concerns about proposed LNG importation projects on U. S. coasts, the Department of Transportation specified the use of a so-called "Gaussian" model (popularly referred to as the MTB or Material Transportation Bureau model) for calculation of the gas dispersion protection zones required by the new regulation. During the same period, the U.S. Coast Guard and GRI sponsored the development at the CHRC of the DEGADIS (DEnse GAs DISpersion) model to describe atmospheric dispersion of denser-than-air gases following accidental release. The principal component of LNG is methane, and although methane at ambient temperatures is lighter than air, the cold methane vapor formed from evaporating LNG is denser than air. DEGADIS is a general purpose dispersion model used worldwide to assess the consequences of accidental releases of hazardous, denser than air, gases and aerosols.

The American Gas Association, under provisions of 49 CFR 193, petitioned the Department of Transportation to replace the MTB model with DEGADIS in the regulation, and this took place in 1992. The DEGADIS model, as compared to the MTB model accounts for

- the effect of gravity on a denser-than-air cloud
- the atmospheric "takeup" of gas by the wind
- a realistic treatment of area, rather than point, sources, and,
- a realistic treatment of time varying releases.

DEGADIS treatment of the effects of gravity and the "takeup" of gas by the wind on the dispersion of gas or aerosol clouds were the principal scientific advances in the model.

Figure 1: Field Test of Effect of Vapor Fence on LNG Vapor Cloud

DEGADIS Limitations

Since its introduction, DEGADIS has been demonstrated to accurately describe gravity spreading and decreased turbulent mixing observed in dense gas clouds. However, as with the MTB model, DEGADIS is limited to the prediction of dispersion of gas clouds released from a flat surface and dispersing in the atmosphere over smooth, obstruction-free terrain. Consequently, the method does not account for effects of terrain and flow alteration by obstacles such as buildings, tanks, and dikes, all of which would be expected to decrease the gas concentrations locally and reduce exclusion distances.

Although this limitation should result in predictions that are conservative (greater dispersion distances), there are important cases where terrain features and or flow obstacles could significantly decrease, or even increase, the dispersion distance. In such instances, DEGADIS predictions could be unrealistic. Although the CHRC has continued DEGADIS development and evaluation for application to other dispersion scenarios (such as jet releases), at present, the model remains applicable only to dispersion over smooth obstacle-free terrain.

Challenges of Physical Modeling

GRI initiated a research project at the CHRC in the mid 1980s, concurrently with the DEGADIS development, to evaluate dispersion models that could account for the effects on dispersion of terrain features and obstacles. Physical (wind tunnel) modeling methods were evaluated, as were the rapidly developing computational fluid dynamic (CFD) modeling methods.

During the last decade, the CHRC has thoroughly evaluated the methods which are potentially applicable to the more complex dispersion problems to which DEGADIS is not applicable. Evaluation of physical and CFD modeling methods has resulted in the definition of several important challenges.

First, it was recognized that physical modeling of dense gas dispersion requires wind tunnel operation at very low speeds. Such low speeds introduce fundamental problems in reproducing the desired turbulent flow properties, in a laboratory gas cloud, that are observed in the atmosphere.

Second, CFD limitations include the requirement for demonstrated turbulence closure models, and, particularly for application to complex terrain and obstacle fields, CFD models require very large computer resources. Fortunately, economical computer resources continue to grow at a rate which seem to insure that the required resources become available by the time the more fundamental requirements, such as adequate descriptions of fluid turbulence affected by density gradients, have been demonstrated.

Third, demonstration of a predictive model requires experimental data, and while many attempts have been made to perform field experiments to obtain such data, the resulting experience is mixed, primarily because of the difficulties in control of the field experiment conditions (Figure 1). It is also very expensive, perhaps prohibitively so, if one wants to demonstrate a model's performance over a range of conditions that match its intended applications.

Development of ULS Wind Tunnel

CHRC, with support from GRI, constructed an ultra-low-speed (ULS) wind tunnel specifically designed to study dense gas dispersion. This wind tunnel is the largest of its kind in the world. The tunnel is used to conduct dense gas dispersion experiments at reduced scale (e.g., 150/1). Although the facility can physically model many LNG and other gas release scenarios with great accuracy, its principal use has been for conducting model experiments that can be simulated directly with CFD models. This method allows the mathematical models to be verified by direct comparison with accurate data at the reduced scale, increasing confidence that the model will accurately describe the physical

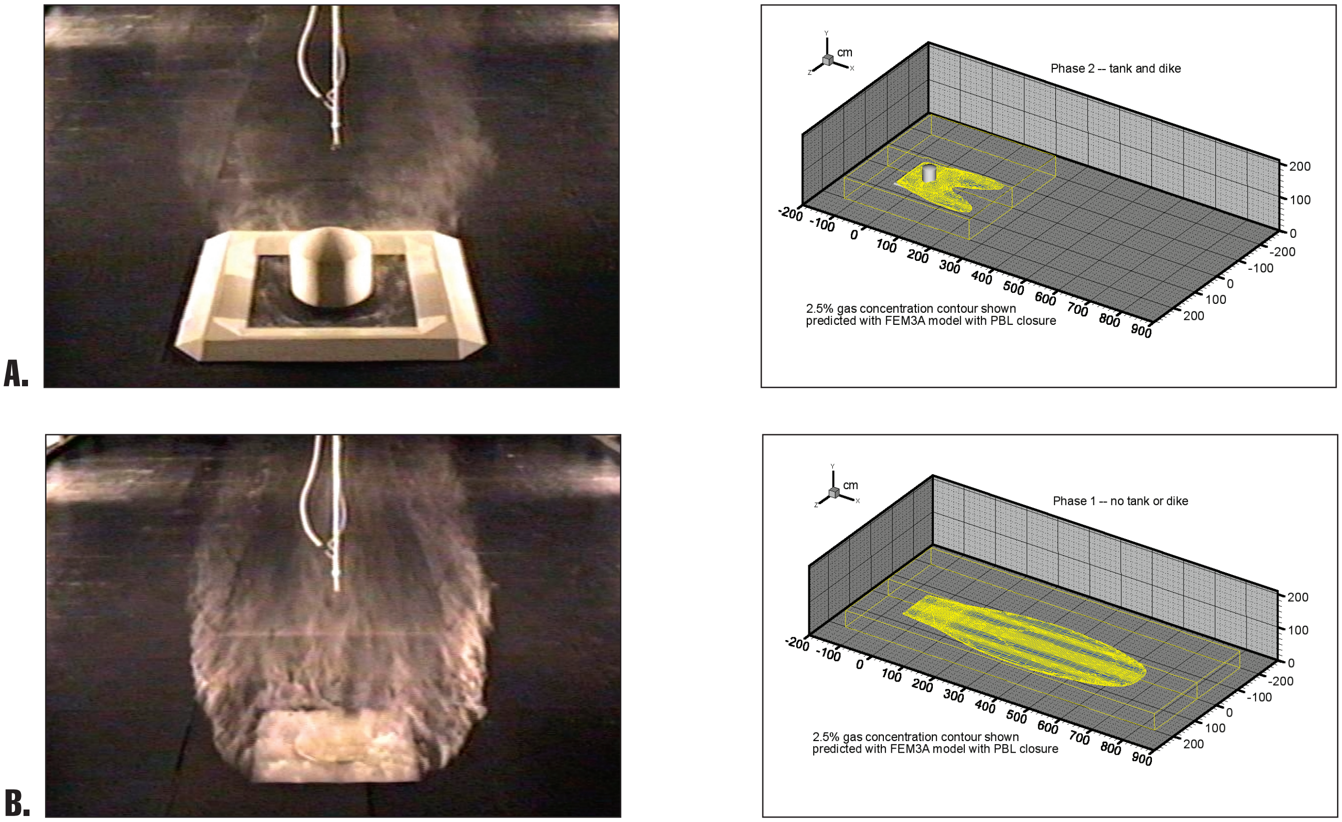


Figure 2: Wind Tunnel Dispersion (A) With and (B) Without Tank and Dike Compared with FEM3A Simulations of the Associated Hazard Zones

phenomena expected in the field. The combined use of CFD tools and the wind tunnel model to validate computer models avoids many of the uncertainties inherent in earlier model validation efforts which relied primarily on difficult and costly field experimentation.

CFD Model Verification Using Wind Tunnel

In 2001 the GTI-CHRC research program completed a five-volume report describing the effort to verify the FEM3A (CFD) model. This model was also developed beginning in the mid 1970s, in response to the same public concerns that drove DEGADIS development. Subsequently, the Department of Transportation revised 49 CFR 193 to allow the use of the FEM3A model to account for the effects of terrain or obstacles on the vapor dispersion distance.

The limits of the vapor cloud extending downwind from a "design" spill into the annular space between a model LNG tank and its dike are illustrated by flow visualization experiments in the ULS tunnel and compared with FEM3A model output (Figure 2). The limiting concentration used to define the cloud corresponds to the 2.5 percent carbon dioxide concentration (carbon dioxide density, at ambient temperature, is essentially identical to LNG vapor density at its temperature of release), were calculated with the FEM3A model.

The model output shows vapor dispersion protection zones predicted with FEM3A for LNG spills corresponding to the wind tunnel scenarios shown in Figure 2, including:

- an area gas source, with tank and dike, with flat, smooth terrain,
- an equivalent area source without a tank or dike and flat terrain.

The FEM3A predictions reveal important reductions in the vapor dispersion exclusions resulting separately from surface roughness and from the presence of the tank and dike, as well as from their combination. Extensive measurements in the CHRC wind tunnel of the gas concentration fields for these experiments confirmed the FEM3A predictions. Such predictions were extremely important to the acceptance by the Department of

Transportation of the FEM3A model for inclusion as an alternate to the DEGADIS model for those cases where the DEGADIS model is not applicable.

Next Steps

The GTI-CHRC partnership is continuing its research into LNG safety. With the renewed global interest in LNG, this research is especially timely. The simulations illustrated above utilize a simple boundry layer turbulence model modified to account for turbulence dissipation due to dense gas effects. Although the simple model has been successful in modeling the effectson disperation of simple obstacle arrays such as a single tank and dike on smooth terain, application of the FEM3A model for more complex obstacle arrays and non-uniform terrain are anticipated to require the use of a higher order turbulence closure model. CHRC is continuing the fundamental research required to verify the FEM3A model for application to more complex scenarios, involving generic hazaradous gases. A "generic" gas dispersion model which can be used to evaluate gas dispersion hazards in complex, realictic scenarios will provide a cost-effective means for evaluating industrial hazards as well as terrorist threats. ■

For more information on any of these models and their application, contact the author, Dr. Jerry Havens, at jhavens@engr.uark.edu

New PRODUCTS, SERVICES & OPPORTUNITIES

Opportunities to Reduce Methane Emissions to be Highlighted at Workshop

The 9th Annual Natural Gas STAR Workshop will be held October 28-30, 2002 at the Houston InterContinental in Houston, TX. The Annual Implementation Workshop provides STAR partners with an opportunity to obtain information about the most current, cost-effective emission reduction technologies and practices, exchange ideas with other STAR partners, and learn about new STAR Program activities and initiatives. It also provides an opportunity for companies interested in joining the program to learn more about it.

The Natural Gas STAR Program is a voluntary partnership between EPA and the natural gas industry, focused on identifying and implementing cost-effective technologies and practices to reduce emissions of methane, a potent greenhouse gas. In 2000, STAR industry partners reduced methane emissions from unit operations and equipment leaks by 34 billion cubic feet (Bcf). At a gas value of $3.00 per thousand cubic feet, these gas savings are worth approximately $102 million.

The program has more than 90 partners across all of the major sectors of the gas industry-production, processing, transmission, and distribution. Currently, the program's production sector partners represent 40 percent of domestic gas production, and the transmission and distribution partners represent 77 percent of transmissions mileage and 51 percent of distribution service connections. The program's partnership with gas processing companies, which was launched in 2000, already represents nearly 60 percent of industry throughput.

For more information on the Gas STAR Program, call Program Manager Carolyn Henderson at 202-564-2318 or visit the program's website at http://www.epa.gov/gasstar/.

NETL Solicits Research Proposals

The Department of Energy (DOE), National Energy Technology Laboratory (NETL), is conducting a solicitation to competitively seek cost-shared applications for research and development of technologies that promote the efficient and sound production and use of fossil fuels (coal, natural gas, and oil). Related information on the Fossil Energy Areas of Interest can be found on the NETL website (http://www.netl.doe.gov) under "Technologies" and on the National Petroleum Technology Office (NPTO) website (http://www.npto.doe.gov) under "Technology Areas".

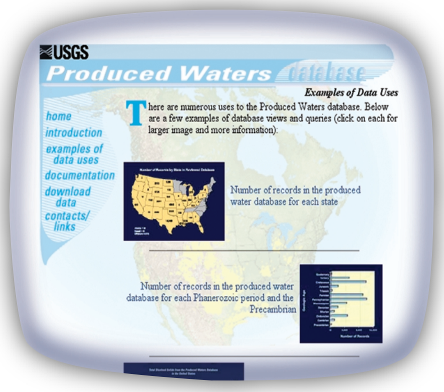
Through this solicitation, NETL expects to support applications in the thirteen separate Areas of Interest, including two that relate specifically to upstream gas exploration, production and processing topics: Topics under Area of Interest 9 (solicitation DE-PS26-02NT41613-09) include Methane Hydrates, Arctic Drilling, Secondary Gas Recovery, and Resource Assessments, and topics under Area of Interest 11 (DE-PS26-02NT41613-11) include Environmental Regulatory Streamlining, Land Access Issues, and Produced Water Issues).

Secondary gas recovery relates to stratigraphic concepts and play analysis, 3-D seismic interpretation, fracture prediction, reservoir modeling, and visualization to reveal the internal architecture of gas reservoirs in existing fields. Resource assessments of major plays or basins will complement past DOE-funded USGS assessments of the Greater Green River, Piceance, Wind River, Bighorn and Crazy Mountain Basins. NETL is interested in assessing onshore deep gas resources (>15,000 feet) and marginal resources (tight gas sands, fractured carbonates, and shales). Specific basins of interest include, but are not limited to, the Hannah Basin, Raton Basin, and Black River/Trenton Play. NETL is particularly interested in assessing basins that can be positively impacted by new technology development.

It is anticipated that there will be from 50 to 75 awards resulting from this solicitation. A minimum cost share is 20 percent of the total estimated cost of the project. It is estimated that $23.85 million will be available for award under this solicitation, subject to the availability of funds. Of this, $2.85 million and $0.35 million will be available for Areas of Interest 9 and 11.

There will be three proposal evaluation periods with submission deadlines of October 28, 2002, February 27, 2003 and October 23, 2003. Award decisions related to these deadlines are expected to be made January 27, 2003, June 3, 2003 and January 26, 2004. More information is available at http://www.fetc.doe.gov/. ■

New PUBLICATIONS



Examples of Data Uses

There are numerous uses to the Produced Waters database. Below are a few examples of database views and queries (click on each for larger image and more information):

Number of records in the produced water database for each state

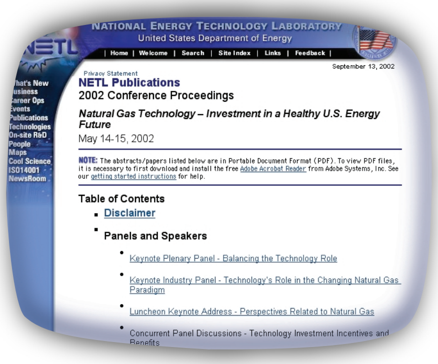
Number of records in the produced water database for each Phanerozoic period and the Precambrian

New From the USGS

A new *Produced Waters Database* (Provisional Release, May 2002) has been compiled and posted online by George N. Breit and Chris Skinner of the USGS. It can be accessed at http://energy.cr.usgs.gov/prov/prodwat/index.htm/. The database presented at this web site is a revision of a database originally compiled at the DOE Fossil Energy Research Center previously located in Bartlesville, Oklahoma. The USGS modified the original database by removing redundancies, verifying internal consistency and adding information to the fields that describe the location, geologic setting, sample type, and major ion chemical composition. A preliminary version of the revised database, a description of the review methods and illustrations of the contained information are presented.

GTI Publication Outlines Drilling and Operations Protocols for Unconventional Canadian Gas

In Canada, development of coalbed methane and shale gas is still in its infancy and information about successful exploration procedures has been limited. A comprehensive guide to planning and implementing a drilling program for these unconventional resources, titled "Drilling Program Planning and Field Operations Protocols for Coalbed Methane and Shale Gas Reservoirs in Canada,"is available from GTI E&P Services Canada, Inc. The publication describes practices and procedures shown to be successful in the Western Canada Sedimentary Basin. It is priced at $125 US ($195 Canadian), plus shipping/postage. Contact Leona Kope, GTI E&P Services Canada, Inc., at 403-263-3000.



September 13, 2002

NETL Publications

2002 Conference Proceedings

Natural Gas Technology – Investment in a Healthy U.S. Energy Future

May 14-15, 2002

NOTE: The abstracts/papers listed below are in Portable Document Format (PDF). To view PDF files, it is necessary to first download and install the free Adobe Acrobat Reader from Adobe Systems, Inc. See our getting started instructions for help.

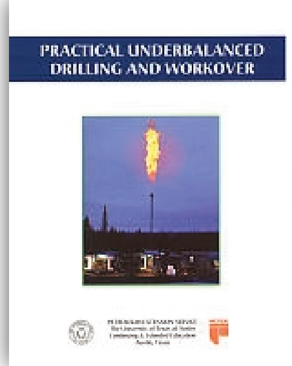
Table of Contents

- Disclaimer
- Panels and Speakers
  - Keynote Plenary Panel - Balancing the Technology Role
  - Keynote Industry Panel - Technology's Role in the Changing Natural Gas Paradigm
  - Luncheon Keynote Address - Perspectives Related to Natural Gas
  - Concurrent Panel Discussions - Technology Investment Incentives and Benefits

Houston Conference Proceedings Available Online

The proceedings of the joint DOE/GTI conference titled *Natural Gas Technology – Investment in a Healthy U.S. Energy Future,* held May 14-15, 2002 in Houston, are now available online at http://www.fetc.doe.gov/ under "Publications." This conference brought together natural gas industry leaders, regional and national government officials, and stae and local lawmakers. Twenty-five presentations, including transcripts of discussion sessions, are available on the website for downloading.

Underbalanced Drilling Text Available



Published by the Petroleum Extension Service at the University of Texas at Austin, *Practical Underbalanced Drilling and Workover,* compiles all the intricacies of underbalanced operations in an easy-to-reference manual. The book covers UBD terms and calculations; UBD guidelines; surface control equipment; downhole tools; gases and equipment; circulation and the fluid column; flow and mud-cap drilling; liquid-gas fluids; foam drilling; air-gas, mist, and foamed mist-drilling; problems; corrosion and scale; rigging up; and flares and flaring. It also includes an appendix, which is the IADC WellCAP curriculum for underbalanced drilling, as well as a glossary and bibliography. The online price is $35, available at http://www.iadc.org/.

Everything You Need to Know About Canadian Formation Water

The 2002 version of the *Canadian Well Logging Society R_w Catalog* is now available.

Over 50,000 data points are included on the CD, in both PDF and XLS formats. The price is only $25 CDN for members and $65 CDN for non-members. Members of the North Dakota Geological Survey may purchase the catalog at the memberprice. To order contact the CWLS office at 403-269-9366. ■

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   - ☐ (84) Operations other than Engineering
   - ☐ (85) Executive Management *(CEO, President, VP, Partner, Director, etc.)*
   - ☐ (86) Management other than Engineering or Executive
   - ☐ (87) Consulting
   - ☐ (88) Purchasing
   - ☐ (59) Other

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   - ☐ (95) Engineering and Construction
   - ☐ (96) Engineering
   - ☐ (97) Water/Slurry Lines
   - ☐ (98) Product Lines
   - ☐ (99) Consulting/Design Engineer
   - ☐ (59) Other

Signature: ____

A27GTP

FAX to PipeLine and Gas Technology at 1-847-647-0830

Events CALENDAR

Information related to workshops, short courses, and other industry meetings.

October 23 - 25	**4th Annual Unconventional Gas and Coalbed Methane Conference, Calgary, Alberta.** Sponsored by PTAC and the Canadian Coalbed Methane Forum. Conatct Kerri Markle at 403-218-7711.
October 28 - 30	**North American Gas Strategies Conference, Calgary, Alberta** Annual gas strategies conference sponsored by Ziff Energy Group. Contact: Paula Arnold at 403-234-4279 or at gasconference@ ziffenergy.com/.
November 11	**RMAG Prospect Property Fair and Technofest, Denver, CO.** To be held at the Denver Convention Center by the Rocky Mountain Association of Geologists (RMAG). For more information phone 303-573-8621 or visit www.rmag.org/ and www.mines.edu/research/PTTC/.
November 11-12	**Gas Shales: Production & Potential Seminar, Houston, TX.** Strategic Research Institute seminar to be held at Renaissance Houston. Contact 212-967-0095 Ext. 271 or visit www.srinstitute.com/.
November 18-19	**Arctic Gas Symposium, Houston, TX.** To be held by the Canadian Institute at the Renaissance Houston Hotel. Phone 877-927-7936 or visit www.CanadianInstitute.com/.

2003

January 28-30	**NAPE 2003 / North American Prospect Expo** Held by the American Association of Professional Landmen at the George R. Brown Convention Center. Contact 817-847-7700 or visit www.napeonline.com/.
February 23-26	**53rd Annual Laurance Reid Gas Conditioning Conference, Norman, OK.** Held at The University of Oklahoma. For additional information, contact Betty Kettman at 405-325-3136 or via e-mail at bettyk@ou.edu/.

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