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Development of a Hydraulic Borehole Seismic Source

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Prepared by

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Development of a Hydraulic Borehole Seismic Source

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Abstract

This report describes a 5 year, \$10 million Sandia/Industry project to develop an advanced borehole seismic source for use in oil and gas exploration and production. The development Team included Sandia, Chevron, Amoco, Conoco, Exxon, Raytheon, Pelton, and GRI. The seismic source that was developed is a vertically oriented, axial point force, swept frequency, clamped, reaction-mass vibrator design. It was based on an early Chevron prototype, but the new tool incorporates a number of improvements which make it far superior to the original prototype. The system consists of surface control electronics, a special heavy duty fiber optic wireline and draw works, a cablehead, hydraulic motor/pump module, electronics module, clamp, and axial vibrator module. The tool has a peak output of 7000 lbs force and a useful frequency range of 5 to 800 Hz. It can operate in fluid filled wells with 5.5" or larger casing to depths of 20,000' and operating temperatures of 170 °C. The tool includes fiber optic telemetry, force and phase control, provisions to add seismic receiver arrays below the source for single well imaging, and provisions for adding other vibrator modules to the tool in the future. The project yielded four important deliverables: A complete advanced borehole seismic source system with all associated field equipment; field demonstration surveys funded by industry showing the utility of the system; industrial sources for all of the hardware; and a new service company set up by our industrial partner to provide commercial surveys.

Acknowledgments

This project was jointly funded by DOE, Chevron, GRI, Exxon, Conoco, Amoco, Raytheon, and Pelton. Many people contributed to the success of this project. We particularly acknowledge the contributions and support of Bjorn Paulsson, Jack Cole, Dale Cox, Sen Chen, Frank Bernhard, Glenn Kirkendall, Larry Lucas, Gary Hobson, Charles Rappleye, Tim Fasnacht, Henry Tan, Kim Mitchell, John Giles, Marion Scott, Gilbert Benavides, Ronald Franco, Jim Uhl, Russ Keefe, and Bruce Engler. This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Author's Note

The views expressed are those of the author, based on his experience and perception of the project, and are not necessarily those of DOE, Sandia, or other project participants.

Contents

Background	1
Other Hydraulic Vibrators	10
Program Details	14
CRADA	14
Development Team:	14
Schedule:	17
Funding:	19
Tool Ownership and Operation	20
Commercialization	20
Modeling and Analysis	22
Tool Design and Fabrication	31
Overview:	31
Cable Head	36
Motor/Pump Module	36
Electronics Module	39
Clamp	49
Axial Vibrator	51
Other Vibrator Modules	60
Single Well Hardware	62
Drawings	63
Overall System	64
Field Tests	77
System Integration and Checkout Tests	79
First Commercial Test	87
Second Commercial Test	87
Third Commercial Test	89
Conclusions	91
References	92
Distribution	93

List of Figures

Figure 1:	Seismic Source and Receivers in Crosswell Configuration	2
Figure 2:	Seismic Source and Receivers in Single-Well Configuration	2
Figure 3:	Seismic Source Project Team, Objectives, and Tool Diagram	5
Figure 4:	Completed Source Tool System Integration Test.....	7
Figure 5:	Output of Chevron Prototype and New Source Tool.....	9
Figure 6:	Hydraulic Seismic Sources	12
Figure 7:	Close-up of Chevron and Conoco Sources	13
Figure 8:	Modeled Transient Force Output.....	23
Figure 9:	Modeled Effect of Air in Hydraulic Oil.....	24
Figure 10:	Modeled Effect of Stroke and Reaction Mass Trade-offs.....	24
Figure 11:	Preliminary Thermal Analysis	26
Figure 12:	Modeled Load Impedance vs. Frequency.....	29
Figure 13:	Modeled Ratio of Clamp Force to Actuator Force.....	29
Figure 14:	Hardware Photographs.....	34
Figure 15:	Hardware Photographs.....	35
Figure 16:	Pelton Control Electronics	42
Figure 17:	Wiring Diagram and Sensor Description.....	43
Figure 18:	Pelton Variable Amplitude Drive to Flatten Force Output.....	45
Figure 19:	Pelton Variable Dwell Producing Flat Energy vs. Frequency Output.....	46
Figure 20:	Fiber Optic Telemetry System	48
Figure 21:	Axial Vibrator Module	52
Figure 22:	Effect of Command Force Level on Force Output	56
Figure 23:	Effect of Reaction Mass Weight	56
Figure 24:	Effect of Hydraulic Supply Pressure on Force Output.....	59
Figure 25:	Progressive Improvements to Team Tool Output	59
Figure 26:	Radiation Pattern of Different Vibrator Modules	61
Figure 27:	Seismic Source Control, Shipping, Recording, and Data Processing Trailer	65
Figure 28:	Fiber Optic Seismic Source Wireline Description.....	70
Figure 29:	Fiber Optic Seismic Source Wireline	71
Figure 30:	Fiber Optic Receiver Cable.....	72
Figure 31:	Wireline Truck.....	74
Figure 32:	Tool on Wireline Being Lowered Into Well	76
Figure 33:	Lifting All Tool Modules Simultaneously Using Strong-Backs	76
Figure 34:	Comparison Test of Surface Vibroseis and Conoco Borehole Vibrator	78
Figure 35:	Allied Signal 48 Sonde Receiver Array.....	80
Figure 36:	Data from Allied Signal Receiver Array and Chevron Prototype Source	81
Figure 37:	La Habra Test Site Overview	83
Figure 38:	Comparison Tests at La Habra Field Site.....	84
Figure 39:	La Habra Test of Team Tool.....	85
Figure 40:	La Habra Test of Team Tool.....	86
Figure 41:	Carthage Texas Test	88

List of Tables

Table 1: Comparison of Chevron Prototype, Original Goals, and Present Tool.....	6
Table 2: Borehole Source Characteristics.....	8
Table 3: Project Timeline.....	17
Table 4: Project Funding	19

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Background

The purpose of this 5 year, \$10 million Sandia/Industry project was to produce a powerful, controllable, fieldable vibratory borehole seismic source, and to make it available to the oil and gas industry.

2-D and 3-D surface seismic surveys are the main geophysical method used in oil exploration and development. They involve the generation of seismic waves at the earth's surface by means of a seismic source, typically a large hydraulic vibrator known as a Vibroseis, or by the use of explosives. These sources are fired at a large number of locations. The resulting seismic waves travel down through the earth, are reflected from subsurface layers, and travel back to the surface where they are recorded by large arrays of seismic receivers such as geophones or accelerometers. These reflections delineate the geologic structure of the formation.

In recent years, geophysicists have developed a new technique, referred to as borehole seismic imaging, to image complicated structures with higher resolution than is possible with surface techniques. Borehole seismic surveys are conducted by placing a seismic source in a well and transmitting seismic energy to an array of receivers located in a second well (cross well surveys) in the same well (single well surveys), or on the surface (reverse vertical seismic profile, RVSP). By comparing the transmitted and received signals, information can be obtained about the formations through which the seismic energy has passed or from which it is reflected. By recording seismic waves from a number of source and receiver positions, an image of the intervening formation can be constructed, much like the surveys performed on the surface. Figure 1 shows a typical crosswell configuration and Figure 2 shows a single well configuration.

The advantages of crosswell surveys over surface surveys are that the source and receivers are located below the surface weathered layers which are very attenuating to high frequencies. This means that much higher frequencies can be propagated (100's of Hz with cross well, compared to 10's of Hz for surface surveys), offering much higher feature resolution. In addition, the source and receiver can be located closer to the formation of interest, the survey can be tied directly to well logs, borehole methods provide a different orientation of seismic energy to the formation, and additional information can be obtained about formation velocities, fractures, and other properties (Williams et al. 1997).

The disadvantages of crosswell surveys are that wells must be located in the area of interest and must be available throughout the time of the survey, the surveys cover a smaller land area, they can take a long time, they are expensive, and they require a very powerful source and sensitive receiver to be useful across typical well separation distances of hundreds to thousands of feet.

By combining the high resolution imaging which is possible using borehole seismic surveys, with traditional surface seismic surveys, the uncertainty and economic risk of drilling can be greatly reduced and the recovery of oil from heterogeneous oil reservoirs can be improved.

Figure 1: Seismic Source and Receivers in Crosswell Configuration

Figure 2: Seismic Source and Receivers in Single-Well Configuration

A major impediment to widespread use of these borehole seismic techniques is the lack of availability of suitable, commercially available borehole seismic sources. Many borehole seismic source concepts have been proposed or developed but few have been widely accepted. Some of the borehole sources that have been developed include air guns, unbalanced motor orbital vibrators, electromagnetic shakers, magnetostrictive vibrators, explosives, sparkers, piezoelectric benders, hydraulic or pneumatic vibrators, weight drop mechanisms, impact hammers, resonant cavities, audio speakers, and other designs (Owen 1995). Some of these sources are commercially available through service companies, others are available only in industry, university, or laboratory research departments. Each of these have advantages and disadvantages.

Most of the currently available borehole seismic sources suffer from one or more of the following disadvantages which limit their utility: the limited or inappropriate frequency range of the sources, the complexity of the tools, the generation of significant tube waves, poor coupling to the formation, difficulty in deploying due to long pneumatic or hydraulic hoses or size or temperature limitations, the high cost of fabricating and fielding the sources and associated surface support equipment, the potential for damaging the wells, and the comparatively low signal output from the sources which limits their use to closely spaced wells. In addition to these tool concerns, there are concerns about the high cost of performing surveys, the loss of oil or gas production while the surveys are performed, questions about how to interpret the data, etc.

It is difficult and very costly to produce a powerful, controlled, rugged borehole source that will fit within the well diameter and stand up to the harsh conditions of typical oil wells. Efforts by oil companies, service companies, and tool suppliers to develop borehole seismic sources with increased range and resolution that are easily fielded and rugged enough for wellbore use have met with mixed success. Given the high cost and long time required to develop these tools, in conjunction with a downturn in oil prices, many oil companies and service companies who had been very active in borehole seismic tool development began to reduce or eliminate these efforts. Those companies who remained involved saw the need to cooperate and pool their efforts in developing improved sources. At the same time, it is in the government's interest to reduce our countries' dependence on foreign oil and to increase the recovery of oil from our reservoirs. By combining the high resolution imaging which is possible using borehole seismic surveys with traditional surface seismic surveys, the uncertainty and economic risk of drilling can be greatly reduced and the recovery of oil can be improved. In the past the DOE laboratories have developed sensitive, high frequency borehole seismic receivers for crosswell applications (Sleepe et al. 1995), and have worked on a number of borehole seismic sources (Hardee et al. 1987), (Cutler et al. 1997). Seismic research and high resolution imaging of underground features also have potential applications in the areas of non-proliferation, underground structure detection, and treaty verification.

Chevron and Sandia presented a joint proposal to the DOE Borehole Seismic Forum, seeking project funding to develop an improved borehole seismic source. The proposal was approved, and Chevron and Sandia signed a Cooperative Research and Development Agreement (CRADA) to begin work on the tool. The CRADA defined project scope, performance requirements, funding levels, and schedule. A number of companies with active programs to develop their own

seismic tools subsequently joined the development team. The Team grew to include Sandia, Chevron, Amoco, Conoco, Exxon, Raytheon, Pelton, and the Gas Research Institute (GRI). This Team included oil company engineers and geophysicists with extensive experience in developing borehole tools and conducting field tests, manufacturers with expertise in advanced actuators and controls, and Sandia specialists in modeling, materials, fiber optics, high temperature electronics and high performance telemetry systems for severe environments. Figure 3 shows the seismic source project team, objectives, and tool diagram.

Our starting point for the project was the Chevron prototype hydraulic vibrator, which they had developed during the 1980's. It is a clamped reaction mass vibrator design. It has a peak output of 3000 lbs, approximately 1500 lbs output force from 30 to 300 Hz, is limited to operation in dry wells cased with 7" casing. The maximum depth is 2000' at ambient temperatures. It has no force or phase control, and is very difficult to deploy due to surface hydraulics and electronics and hydraulic hoses and deployment wirelines that have to be bundled together and fed down the well.

Team members evaluated the prototype Chevron tool, established preliminary requirements and designs, discussed the features of their existing borehole sources, and met with suppliers and engineers to determine what was feasible. A detailed performance specification was developed which included specific requirements, design constraints, results of initial modeling, predicted tool performance, and specified operating environment. Team members attended monthly design meetings, reviewed all hardware designs, tool drawings and test results, visited each other's facilities, conducted field tests of their existing borehole sources and conducted tests of the new hardware.

The original goals established for the new source include the following:

1. High output force (peak of 6000 lbs , goal of >1500 lbs to >600 Hz)
2. Wide bandwidth, including low frequencies for long propagation distance, and high frequencies for high spatial resolution (usable bandwidth 10 to > 600 Hz)
3. Multiple Axes of vibration (we fabricated only a vertical axis module but made provisions for additional vibration axes modules)
4. Vibratory, non-impulsive source
5. No volumetric change, to minimize tubewaves
6. Clamped for good coupling to formation
7. Fail safe operation and retraction
8. Controllable seismic output
9. Tool small enough to fit all weights of 5.5" casing (4.40" tool OD)
10. Operable at high temperature (>150 °C, with goal of 200 °C)
11. Easy deployment on heavy duty wireline with no hoses to the surface

In addition to these original goals, we later expanded the applications for the tool and included the following goals:

12. Single well imaging capability with receivers hung below the source
13. Deployable in deeper wells (to 20,000')
14. Tool and service commercially available

Development of a Multi-Component Borehole Seismic Source

An Industry, Sandia, GRI Project

Figure 3: Seismic Source Project Team, Objectives, and Tool Diagram

The new tool was successfully developed, along with all of the associated surface support equipment. It underwent initial operational tests, and then was used in three commercial surveys. Figure 4 shows the completed tool being deployed in system integration tests at Chevron's La Habra California test site.

The new tool has a peak output of 7000 lbs force, can operate in fluid filled wells cased with 5.5" casing and larger, at depths to 20,000' and temperatures up to 170 °C. In addition, provisions were added for fiber optic telemetry and for attaching seismic receivers below the source to allow single well imaging, as well as crosswell imaging (Paulsson 1996).

Table 1 compares the features of the Chevron prototype tool, the original goals for this project, and the present tool. Table 2 lists the basic tool characteristics.

Table 1: Comparison of Chevron Prototype, Original Goals, and Present Tool

<u>Feature</u>	<u>Chevron Prototype</u>	<u>Original Goal</u>	<u>Present Team Tool</u>
Maximum deployment depth	2000'	11,000'	20,000'
Use in fluid filled wells	No	Yes	Yes
Peak Force (lbs)	3000	6000	7000
Bandwidth (Hz)	10 to 600	5 to 1400	5 to 800(limit of tests to date)
Maximum ambient temperature	100 °C	125 °C	170 °C
Minimum well casing diameter	7"	7"	5.5"
Hoses to surface	Yes	No	No
Fail safe clamp	Yes	Yes	Yes
Force and phase control	No	Yes	Yes
3-axes vibration	No	Yes	No (Plans for 1999)
Tool commercially available	No	Yes	Yes
Service commercially available	No	No	Yes
Allow receiver in same well	No	No	No (Yes in 1998)

**Figure 4: Completed Source Tool System Integration Test
La Habra, California, February 1997**

Table 2: Borehole Source Characteristics

Tool Diameter	4.40" (axial vibrator module 4.56")
Tool Length	3 modules, total length 34 feet
Tool Weight	1500 lbs
Hydrostatic Pressure Limit	12,000 psi
Maximum Ambient Temperature	150 °C Cable, 170 °C electronics, 200 °C tool
Internal Temperature Rise	50 °C
Deployment	Special Armored Fiber Optic Wireline
Cable Length	20,000 feet
Cable Breaking Strength	64,000 lbs
Clamp	Hydraulic piston clamp, with redundant fail safe retraction
Drive Signal type	Swept frequency, fully programmable
Useful Frequency Spectrum	5 to 800 Hz
Peak Force	7000 lbs
Radiation Pattern	Vertically oriented axial point force
Material	15-5 PH Stainless Steel

Figure 5 compares the measured output of the Chevron prototype tool and the new source tool that the team developed.

This project yielded four important deliverables:

1. A complete advanced borehole seismic source system with all associated field equipment
2. Field demonstration surveys funded by industry to show the utility of the data
3. Commercial sources for all of the hardware developed
4. A new service company set up by our industrial partner to provide commercial surveys for any interested company.

Figure 5: Output of Chevron Prototype and New Source Tool

Other Hydraulic Vibrators

Chevron Prototype Source

Chevron had developed a prototype axial vibrator, which had been built by Moog during the mid 1980's. It consists of a hydraulically actuated clamp, a servo valve, and a reaction mass. It was powered by a hydraulic pump located at the surface, and connected to the downhole vibrator by high pressure hydraulic hoses. It was deployed in wells using a wireline, with the high pressure hoses clamped to the wireline. It was used extensively in surveys at a number of sites around the world. It was operated in a swept mode and produced a peak output of 3,000 pounds force, sweeping from 10 to 640 Hz. The force output curve for the prototype source is shown in Figure 5.

This prototype source produced excellent data, but had a number of limitations. It was not watertight, and so it could not be deployed in fluid filled wells. It was limited by the hydraulic hoses and surface hydraulic power supply to a depth of 2,000'. Its maximum operating temperature was 100 °C. It could only fit in 7" or larger well casing. There was no force or phase control of the output. Since this was a prototype, company owned tool, there were no commercial companies available to supply spare parts, additional tools, or field services. As a result, Chevron began an effort to produce an improved, fieldable hydraulic borehole seismic source that would overcome these limitations. Their prototype served as the starting point for the development of the advanced seismic source.

Conoco Axial Vibrator

Conoco had a very active borehole tool development program. They had produced unbalanced weight orbital sources, magnetostrictive sources, and hydraulic vibrators. At the time we started this project, they were working on an axial vibrator module similar to what we had proposed. During the first year of the project, they finished fabrication and preliminary laboratory and field testing of their module. They were also designing and purchasing a large, heavy duty 10,000' wireline and draw works to use in deploying and powering several of their borehole sources. They had not developed a downhole hydraulic power supply or electronics, so the testing was done near the surface. They were very interested in being involved in our project and in adapting the downhole hydraulic power supply and electronics we were developing to their source.

Vibroseis

Conoco had invented the Vibroseis surface hydraulic vibrator widely used in conducting surface seismic surveys. It consists of a very large heavy duty truck with a high performance hydraulic actuator. On one end of the actuator is a base plate that contact the ground. On the other end is a reaction mass weighting thousands of pounds. When the actuator pushes against the reaction

mass, an equal and opposite force is generated against the base plate, generating seismic signals in the ground. A number of manufacturers produce Vibroseis equipment. In order to transmit large forces into the ground, these trucks are very large and heavy. The near surface layer of the earth is very attenuating to high frequency seismic waves. This, combined with the large size and weight of these tools limits their useful frequency output to approximately 70 Hz, although some have been designed to operate up to higher frequencies to approximately 150 Hz.

Figure 6 shows these three hydraulic seismic sources, and Figure 7 shows a close-up view.

Hydraulic Seismic Sources

Chevron Source

3000 lbs force peak

10-640 Hz

(No force or phase control, dry wells only
hose limit operation to 2000', single axis)

Conoco Source

6000 lbs force peak

20-640 Hz

(Single axis, designed for liquid wells to 10,000' deep, assuming downhole electronics and power supply are developed)

Vibroseis

30,000 lbs force peak

20-150 Hz

Figure 6: Hydraulic Seismic Sources

Figure 7: Close-up of Chevron and Conoco Sources

Program Details

CRADA

After several attempts to partner with other laboratories, commercial tool companies, and oil field service companies, Bjorn Paulsson of Chevron approached Sandia National Laboratories with a proposal to build an advanced seismic source. A joint project was proposed in 1992 to the Borehole Seismic Forum, a trade association of 27 industrial companies and 9 DOE laboratories, soliciting Department of Energy funds to help produce an improved borehole seismic source tool. The proposal was approved. Sandia and Chevron signed a Cooperative Research and Development Agreement (CRADA #92-1074). The CRADA included a statement of work, performance goals for the tool, development schedule, anticipated funding, addressed hardware ownership and intellectual property rights, provided for protection of proprietary information, and made provision for adding additional team members.

A Statement of Work was written and agreed upon by the design team. It listed the details of the hardware modules, including a downhole hydraulic power supply operated on a wireline, downhole control electronics, a clamp, and three different hydraulic actuators to generate axial and two radial source components in the formation. It also detailed the temperature, pressure, corrosion and safety requirements, and the required tool force vs. frequency response. A purchase requisition was written and sent to a number of potential industrial tool developers to participate in the design and fabrication. We received a positive response to our RFQ and began contract negotiations.

Development Team:

Sandia

Sandia had prior experience in development of advanced hydraulic systems, high-temperature electronics, borehole seismic sources, and high-frequency borehole seismic receivers. They helped develop the overall system design, performed numerical modeling, provided expertise in high temperature electronics, fiber optics, telemetry, and materials, placed and oversaw the contract for and funded the fabrication of much of the downhole tool, including the axial vibrator, clamp, and electronics module and provided program management. Bob Cutler was the project leader at Sandia.

Chevron

Chevron had built the original prototype tool and had extensive experience operating this tool in oil fields around the world. They supplied drawings, test data, and their operational experience with this prototype. They provided a large portion of the funding for the project, and also solicited additional project partners and funding. They contracted for the design and fabrication of a number of pieces of the downhole and uphole seismic system, including the motor/pump module, cablehead, wireline, and surface support equipment. They provided a test site and field

support, and also helped with legal work. Later, Chevron helped to establish a commercial company to deploy the source in commercial surveys. Bjorn Paulsson was the project leader at Chevron, and later left Chevron to become president of the newly established service company, Paulsson Geophysical Services, Inc. (P/GSI).

Los Alamos

Los Alamos National Laboratory was involved in early discussions on the source and helped to define the tool specifications. They had anticipated working extensively on the project because of their background in high temperature motors for geothermal applications. However, due to personnel changes and changing program priorities, they chose not to continue participating after the first year of the project.

Conoco

Shortly after the Borehole Forum presentation, Jack Cole, the project leader for Conoco's borehole seismic development group, approached Chevron and Sandia and suggested that Conoco join the project. Conoco had been very active in developing borehole tools and had built and tested a number of seismic sources and receivers. Dale Cox at Conoco also had extensive experience in processing crosswell data. They were in the process of developing a similar hydraulic seismic vibrator, and were interested in using the downhole electronics and the hydraulic motor/pump assembly that would be developed on this project to operate their axial vibrator module. In addition, they were fabricating a large custom 10,000' wireline and wireline truck capable of providing power for downhole sources. Conoco provided engineering support, a test site, field support, data processing, and details of their seismic sources. Due to the long time required to form a CRADA, Conoco, as well as the others who joined the team later, joined the project through contracts or other separate legal agreement with Chevron or Sandia, rather than as CRADA signatories.

Raytheon

After finalizing the requirements for the downhole tool, Sandia wrote an RFQ seeking interested industrial companies to participate in the design and fabrication of the tool. Raytheon (formerly E-Systems, Montek Division) was the successful bidder, and a contract, AF-8334, was placed with them. Raytheon is a world leader in high performance, high reliability hydraulic systems for commercial aircraft. The contract included substantial cost share by Raytheon in the development and fabrication of the source, and throughout the project they were an integral part of the project team. Raytheon did much of the modeling, mechanical and electrical design, and all of the tool mechanical fabrication and testing. They also provided field support. Frank Bernhard and Glenn Kirkendall were the project leaders at Raytheon.

Pelton

In 1993 Chevron placed a contract with Pelton to design and fabricate the required vibrator control electronics. Pelton is the world leader in control electronics for large surface hydraulic seismic vibrators, and had extensive experience in swept frequency control for these applications. Pelton designed and fabricated the uphole and downhole control electronics, including the sweep generator, force and phase control, tool status diagnostics, etc. They provided laboratory and

field test support. Pelton contributed a large amount of cost sharing in the development. Kim Mitchell and John Giles were the project leaders at Pelton.

Amoco

In late 1993, Amoco joined the project. They were primarily interested in using the source for large area Reverse Vertical Seismic Profiles (RVSP) and in fracture detection. They had worked extensively with Conoco in developing seismic receivers and in conducting crosswell surveys. They also had extensive seismic modeling and analysis capabilities. They provided funding, geophysical modeling, field support, and fabrication support through their shops. Henry Tan was the project leader at Amoco.

Exxon

In 1994, Exxon joined the project. They had been very active in developing and fielding borehole seismic sources and receivers. They were primarily interested in using the tool in a single well mode for imaging salt dome flanks. In this mode, both the source and an array of seismic receivers are deployed in the same well. Exxon provided their 5 level clamped receiver array for use on the project, as well as significant funding to incorporate the single well imaging features into the tool. Sen Chen was the primary investigator from Exxon.

GRI

In 1994, GRI joined the project. They were interested in deploying the source in very deep gas wells, and also in making crosswell surveys using this source commercially available to the oil and gas industry through a service company. They paid for a special, heavy duty 20,000' fiber optic wireline, draw works, and other equipment to provide this deep well capability. Tim Fasnacht was the project leader at GRI.

Suppliers

In addition to these Team members, other major suppliers included MTI for the high efficiency electric motors and motor controller, Vickers for the hydraulic pump, Vector Cable for the specialty fiber optic wirelines, and Dynacon for the draw works. Several of them provided significant cost sharing on their contracts.

Each of the companies that joined the project brought additional resources including funding, modeling capability, engineering support, borehole tool experience, field support, shops, and receiver technology. Their involvement and funding permitted expanding the scope of the project to include single well imaging, fiber optic telemetry, use in deep wells, and commercial availability of the system and of field surveys.

The project team held frequent technical design, modeling, programmatic, and budget meetings with all members of the project team. It became apparent that we needed a complete crosswell seismic system including the seismic source, high frequency receivers, surface support equipment, software, and data processing. Therefore, we also held meetings on strategic issues for borehole seismology, including discussions of the source, receivers, recording systems, processing and interpretation software, various imaging applications, the economics and commercialization of

borehole tools and surveys, finding appropriate field test sites, and discussions of additional cooperative R&D possibilities among the team members.

Decisions on both technical and programmatic issues were decided by a vote of all team members. We also presented the status of our work and our proposals for yearly funding at the annual DOE Borehole Seismic Forums and at additional DOE reviews and geophysical technical meetings. The project generated high interest from a number of oil companies, service companies, and geophysical researchers.

The project occurred during a time when a number of oil companies were downsizing their research departments and eliminating their hardware development capabilities. Our industrial partners experienced internal reorganizations, budget cuts, and reductions in personnel, equipment and facilities, but they remained committed to the project and worked on ways to maintain their level of support.

Schedule:

The project was initiated in late 1991 and in 1992 we developed a conceptual design and established the CRADA. During 1993 we assembled the project team, began computer modeling, placed contracts, and designed and fabricated the axial vibrator module. During 1994 we designed the electronics module, motor/pump module, clamp, cablehead, wireline, uphole motor controller and uphole electronics, and tested the axial vibrator module. During 1995 we fabricated the electronics module, motor/pump module, clamp, cablehead, wireline, uphole motor controller and uphole electronics. In 1996 all of the surface support hardware was completed. In 1997 the entire system was integrated and underwent system checkout tests, and the tool was used in commercial surveys funded by industry. Details of the schedule are shown in Table 3.

Table 3: Project Timeline

<u>Year</u>	<u>Task</u>	<u>Completed</u>
1991		
	Project Start	Sept
1992		
	Establish preliminary tool requirements	Jun
	Conceptual design and component sizing	Sep
	Establish CRADA	Dec
1993		
	Complete technical specification for source	Feb
	Conoco joins team	Feb
	Place Sandia/Raytheon contract for source	Jun
	Place Chevron/Pelton contract for electronics	Jun
	Hydraulic, thermal, dynamic modeling started	Jun
	Begin motor/pump module design	July
	Detailed design of axial vibrator module	Aug
	Begin clamp design	Aug

	Fabricate 10,000' wireline, cablehead and draw works	Aug
	Field test Conoco and Chevron prototype vibrators at Conoco	Oct
	Pelton lab test electronics available	Dec
	Amoco joins team	Dec
1994		
	Fabricate axial vibrator module	Jan
	Field test axial vibrator module with Chevron clamp, surface hydraulics, and Pelton breadboard electronics	Feb
	Decision to use research electric motor	Feb
	Exxon joins team	Apr
	Decision to use fiber optic wireline	May
	GRI joins team	June
	Pelton brassboard electronics available	Dec
	Clamp design complete	Aug
	Electronics module design complete	Nov
1995		
	20,000' wireline design complete	April
	Fabricate clamp	Nov
	Motor/Pump module design complete	July
	Cablehead design complete	July
	Fabricate electronics module	Dec
	Fabricate 20,000' wireline and truck	Sep
	Fabricate cable head	Sep
	First complete tool test at Raytheon	Nov
	Preliminary design of single well axial vibrator	July
	Begin commercialization	June
1996		
	Fabricate surface support hardware	May
	Fabricate motor/pump module	June
1997		
	Fabricate shipping containers, dummy tool, fiber optic wireline for receivers, integrate recording and processing equipment, integrate receivers	Jan
	Test complete single axis tool at La Habra test site	Feb
	First commercial survey Carthage Texas	May
	Second commercial survey Bayou Choctaw	June
	Third commercial survey	Aug
	Design dual axis horizontal point force vibrator module	May
1998	Fabricate single well version of axial vibrator	TBD
	Design complete three component source	TBD
1999	Fabricate complete three component source	TBD

Funding:

The project funding consisted of DOE funds obtained annually through the Borehole Seismic Forum (formerly the Crosswell Forum), oil industry funds and in-kind services, and commercial company cost sharing. Originally it was estimated that DOE would contribute \$1,700 K and that Chevron would contribute \$1,000 K to the project. The tool design and hardware fabrication ended up being much more expensive than originally estimated. In addition, changes in the technical design of the tool (including changes in materials, adding fiber optic telemetry, incorporating single well capability, developing an advanced high efficiency motor, moving to a smaller tool diameter, etc.), in the level of tool desired (production ready tool including spare parts vs. field demonstration hardware), and amount of support equipment (uphole power supply, receiver array, 20,000' wireline and truck, dummy tool, processing equipment, shipping containers, etc.) led to much higher costs. As the membership of the project Team changed, and as the goals, hardware costs, and scope of work changed, the associated funding also changed. While it is difficult to accurately assess all in-kind funding, labor, etc., when there are multiple companies involved, the overall funding for the project, including both cash and in-kind, was estimated in early 1997 to be as follows:

Table 4: Project Funding

<u>Agency</u>	<u>Funds</u>
DOE	\$3,600 K
Chevron	\$1,470 K
Conoco	\$ 600 K
Amoco	\$ 150 K
Exxon	\$ 900 K
GRI	\$1,088 K
Raytheon	\$1,293 K
Pelton	\$ 450 K
MTI	\$ 400 K
Vickers	\$ 50 K
TOTAL	\$10,001 K (DOE \$3,600 K, Industry \$6,400 K)

A number of things were done throughout the project to adjust for changing costs and funding levels. Chevron, Amoco and Conoco did some of the machining in their shops. The manufacturing companies provided in-kind cost sharing on their contracts. Chevron contracted for many of the pieces machined outside, and several of the team companies provided field support personnel and equipment.

Tool Ownership and Operation

One of the provisions of the CRADA was that whichever party paid for a given piece of property would own it, and that all jointly funded property would be owned by the government. This led to a decision by several team companies to fully fund particular pieces of the system, rather than contributing to all of the tool. Some portions of the overall seismic source system, including the clamp, axial vibrator module, and electronics module, were developed by Raytheon under Sandia contract AF-8335, and are the property of Sandia. Other portions, including the motor/pump module, wireline, cablehead, wireline truck, uphole electronics, Pelton downhole electronics, and receivers were procured by Chevron and Chevron's industrial partners under contracts with Pelton, Raytheon, Vector, Dynacon, and other companies, and this hardware belongs to Chevron, GRI, Exxon and others. Paulsson-Geophysical Services, Inc. (P/GSI), a new service company founded by our former Chevron CRADA representative, Bjorn Paulsson, has negotiated ownership or use rights for this equipment to perform demonstration surveys with the seismic source.

In 1996 Amendment # 1 was written to the CRADA and signed by both parties. It updated the statement of work to reflect the technical changes to the project, which included use of fiber optic telemetry, using separate vibrator modules, adding single-well capability, using an R&D motor, etc. It revised the schedule to match the actual fabrication schedule. It revised the funding to match the actual funding by Chevron and Sandia and also noted the funding provided by the other Team companies who were not signatories to the CRADA. It added an Appendix C which provided for loaning the DOE owned equipment produced by this project to Chevron and their subcontractors, including P/GSI, for use in demonstration surveys. And it extended the duration of the CRADA from 48 months to 60 months.

Commercialization

One of the expanded goals of this project was to make this technology commercially available to the oil industry. Another was to perform field tests that would demonstrate the value of borehole seismic surveys to the oil company business units.

We began discussing a commercialization plan for the project and the involvement of a service company at our first meetings in January, 1993. Western, Schlumberger, and Halliburton had worked on various borehole seismic source projects in the past. Bjorn Paulsson had personally worked with Halliburton on a borehole seismic source, and we also had several discussions with Western about our project. However, the large service companies indicated that they were not interested in becoming involved in a project that did not yet have an established commercial market. They stated that any tool that doesn't run on 7 conductor wireline is almost automatically rejected. They said that they would likely re-engineer any tool that we developed to increase life, user interface, and deployment. They suggested that we work with a smaller service company, build our tool, perform 10-12 surveys, acquire and process some field data, answer some geophysical questions, and then see if there is a market.

Bjorn Paulsson had spearheaded this project internally at Chevron and with various other organizations since the mid 1980's. In June 1994 he presented a commercialization plan to his management at Chevron. The plan involved his leaving Chevron and setting up an independent service company to provide field services for demonstration tests and commercialization of this source. His new company would initially use the Team hardware, and later purchase its own set of hardware. Paulsson's management was very supportive. In September and October 1994 he and his management met with Sandia, GRI, Exxon, Conoco, Amoco, and Raytheon to present the plan. When he first presented this commercialization plan to the source development team, they had some reservations about not having a larger, established service company involved, but agreed to his plan. Bjorn Paulsson conducted a market survey and began developing a business plan and working out the details and agreements necessary to implement this plan.

Paulsson Geophysical Services, Inc. (P/GSI) was incorporated on 6/30/95 with the support and concurrence of Chevron management. Agreements were reached for all of the Chevron and GRI owned source equipment to be transferred to P/GSI for use in the surveys. This includes the 20,000' wireline, wireline truck, surface support equipment, and motor/pump module. In addition, Chevron transferred several Chevron owned well logging trucks, recording trucks, and other field equipment to P/GSI. The Sandia owned portions of the hardware were loaned to Chevron who in turn loaned them to P/GSI. These include the axial vibrator module, electronics module, and clamp. Chevron also provided start-up funding for the company and agreed to fund several field surveys.

P/GSI has conducted three commercial surveys, and has a number of additional surveys planned. They are coordinating all of the system integration work, solving equipment problems encountered during system start-up, working on equipment upgrades, and planning the development of new modules, using industry funding.

With the establishment of this service company, surveys with this new source will become commercially available. In addition, Raytheon and Pelton will sell identical hardware to, and service equipment for, any interested company.

Modeling and Analysis

Hydraulic Modeling

Raytheon has extensive hydraulic modeling capability using in-house programs written to model their hydraulic products for aeronautical applications. They performed a significant amount of hydraulic modeling in preparing their response to the contract RFQ, and then throughout the project continued to model various design tradeoffs. As the project progressed they incorporated test data from the direct drive servo valve (DDSV), axial vibrator actuator, and hydraulic pump into their overall system hydraulic models.

When the axial vibrator was built and tested, the output matched the model well at low frequencies, but at higher frequencies the output dropped off significantly below the modeled output. In addition, the data showed a notch in the actuator output force caused by the hydraulic volume and sprung weight resonance.

A number of issues were investigated to determine the reasons for the low output at higher frequencies. Raytheon modeled the effects of using a lighter reaction mass, shorter stroke actuator, and shorter and lighter overall tool on the output force and bandwidth, including the effects of dead oil volumes and of air in the oil, to determine if we could build a higher frequency version in the future. A few sample plots from these studies are included.

Raytheon modeled the effect of air in the hydraulic oil, and found that it had a much larger affect on the high frequency output, due to the decreased bulk modulus of the oil, than either the weight of the reaction mass or the length of stroke of the actuator. Figure 8 shows the modeled transient force output with and without air entrainment. Figure 9 shows the modeled force vs. frequency for varying amounts of air in the oil. Air in the system decreases the Q, and hence the magnitude of the output following the notch, and shifts the center of the first frequency peak, but doesn't shift the notch. Although we had no evidence that there had been air in the oil during the prior tests, we decided to re-test the tool and then to de-aerate the fluid under heat and vacuum and test it again to see if this had contributed to the lower than expected output at high frequency. Raytheon determined that we could decrease the actuator swept volume thereby reducing the volume of oil and increasing the system stiffness. This would improve the high frequency response without sacrificing output at low frequencies. With the present ± 0.575 " stroke the oil stiffness is 600 ksi. For a stroke of ± 0.200 " this increases to 1,000 ksi. They found that the reaction mass weight could not be decreased appreciably without adversely affecting the low frequency output of the source. Figure 10 shows the modeled effect of some of the trade-offs in stroke length and reaction mass weight.

Raytheon modeled the effects of varying ratios of the directly excited tool mass (the reaction mass) to the indirectly excited tool mass (the portions of the tool that are not decoupled from shaking, including the clamp, surge chamber, axial vibrator housing, and other tool modules).

NLAS421N 1 STAGE
RUN: 05/02/94
DATA FILE: B:\STORES1.DAT

TRANSIENT PLOT

E-SYSTEMS, INC.
MONTEK DIVISION
ENGINEERING

REMARKS- BASELINE FORCE OUTPUT, 10-640 HZ, 1 SECOND, NO AIR ENTRAINMENT

NLAS421N 1 STAGE
RUN: 05/02/94
DATA FILE: B:\STORES1.DAT

TRANSIENT PLOT

E-SYSTEMS, INC.
MONTEK DIVISION
ENGINEERING

REMARKS- FORCE OUTPUT WITH 2% AIR ENTRAINMENT

Figure 8: Modeled Transient Force Output
a) No air in hydraulic fluid
b) 2% air in hydraulic fluid

**Modeled Effect of Air in Hydraulic Oil
on Actuator Output**

Figure 9: Modeled Effect of Air in Hydraulic Oil

**Modeled Effect of Stroke and
Reaction Mass Trade-offs**

**Figure 10: Modeled Effect of Stroke
and Reaction Mass Trade-offs**

They also modeled the effects of operating at various hydraulic system pressures, adding damping orifices, changing the bulk modulus of the fluid, etc. They found that including harmonics had almost no effect on modeled force output since the harmonic distortion of our tool was already low. In addition to the axial vibrator model, they also modeled the output from a proposed horizontal vibrator module, a hydraulically pulsed clamp module, a torsional reaction mass vibrator module, the hydraulic pump, etc. They investigated the effects of high viscosity oil and low back-pressure on cavitation in the pump, and also the need for surge suppressers.

Thermal model

Sandia performed a preliminary thermal analysis of a high power seismic source in a fluid filled cased borehole before the motor and pump were selected. To be conservative this analysis assumed that all of the average power sent downhole would be converted to heat, that there was no large scale convection outside of the length of the tool, and did not include the heat capacitance of the volume of oil surrounding the tool. The model was based on 6000 W continuous heat generation, assumed to be the average energy input over the cycle times. Figure 11 shows the modeled temperature rise in a fluid filled borehole at the casing/cement interface. This figure shows a temperature rise of nearly 100 °C after an hour. Raytheon found information on heat loss in typical 15 hp motors, and modeled the internal temperature rise within the motor/pump module with re-circulated cooling fluid. They calculated that the internal motor temperature would rise a maximum of 25 °C above the well-bore fluid temperature. Sandia's model predicted a maximum temperature difference between the tool housing and the well casing of 17 °C. So, a worst case maximum temperature within the tool would be 100 °C + 25 °C + 17 °C = 142 °C above the initial ambient well temperature. Clearly this would be unacceptable in wells with high ambient temperatures. This model was a worst case scenario, since at these temperature differences there would be significant convection currents beyond the heated length of the tool, and to be conservative this model had ignored the heat capacitance of the oil in the wellbore. The model showed that there was potentially a significant thermal problem, that the temperature rise in the tool was directly proportional to the power input to the tool, and that it was important to minimize the energy sent downhole through the use of efficient motors, pumps and operational procedures. In discussions with manufacturers of electric motors for downhole pumps we were informed that without forced fluid flow in the wellbore past the motors that the motors quickly overheated and burned up. This led us to the decision to develop a very high efficiency electric motor that would minimize the heat generated in the wellbore. With the incorporation of these changes in the design, including the use of a high efficiency motor and circulating cooling fluid within the tool, the steady state temperature increase of the well fluid surrounding the tool was found in testing to be only 10 °C.

Cylindrical geometry considered in the thermal analysis

Dimensional temperature rise of well casing using NEKTON (two-dimensional conduction). Also plotted is an approximate analytical one-dimensional solution

Figure 11: Preliminary Thermal Analysis

Economic Modeling

Several of the team members had conducted in-house economic analysis on the benefits of borehole seismology and felt that if the source operated as we intended that it could make borehole seismic data extremely valuable. Some team members felt that while the majority of the wells in the U.S. are relatively shallow, that the real economic motivation for borehole seismology was in deep, expensive wells. In shallow, less expensive wells the cost of a crosswell survey is a substantial fraction of the cost of a new well. Much of this cost is due to the long field time required to acquire a full survey. This could be dramatically reduced by using a large array of seismic receivers. A number of groups are presently working on developing such arrays (see the Receivers and Geophysical Tests sections of this report).

Amoco has a large on-going effort to combine data from core samples, well logs, EM, borehole seismic, VSP, surface seismic, and production logs. They are using geostatistics and running multiple Monte Carlo simulations to get a better bound on net worth vs. probability. Amoco has done studies of uncertainty in EOR production rates with and without crosswell data (simulated). The uncertainty over ~5000 days without crosswell data was ~18%, but was reduced to 4% with the simulated crosswell data using 10 different simulations. They evaluated the validity of their economic model with real crosswell data and with well histories. They also evaluated the relative economic benefit of crosswell data and 3D seismic.

Bjorn Paulsson created a business plan for his new company, and as background to that did a market survey and economic analysis of various borehole applications. His conclusions were that the major market for crosswell seismic is in deep wells and for mapping of fractured reservoirs, that the single well seismic market is in the Gulf of Mexico doing salt dome reflection imaging and fault mapping, and that the other big market for this source is in reverse vertical seismic profiling.

Seismic Modeling

Amoco modeled the effects of the well casing, cement, and formation velocity on the radiation pattern and transmitted amplitude of the source output for both isotropic and anisotropic conditions. For example, there was a modeled amplitude reduction of ~20% going from un-cased to cased holes in limestone with $V_p=20,000$ ft/sec and $V_s=9,300$ ft/sec. For sandstone with $V_p=13,900$ ft/sec and $V_s=9,900$ ft/sec the amplitude reduction was much smaller (less than 10%). Bjorn Paulsson had a model done of the radiation pattern from his prototype source which suggested that the casing and cement do not affect the radiation pattern for the axial vibrator below 2000 Hz.

Amoco's modeling also showed the need for a multi-component source and the requirements for high frequency output in order to image thin bedded layers. The vertical resolution limit is directly proportional to the formation velocity and the well separation, and inversely proportional to the upper frequency limit of the received data and to the vertical extent of the survey. Therefore, the resolution can be improved by using a combination of higher source frequency and larger vertical aperture. This becomes more important as the well separation increases. They showed that with a 50 to 500 Hz bandwidth we can not image thin channel sands with an average thickness of 10 feet. However, with a 50 to 1000 Hz bandwidth the chances of imaging these channel sands increases significantly.

Much of our effort was directed at achieving as high an upper frequency as possible. However, there are many trade-offs. Since higher frequencies are much more attenuated by the formation than low frequencies, it is imperative to have a very broad spectral output. In some locations, regardless of the strength of the source, the upper frequency limit that can be transmitted is limited to less than 100 Hz, and in some areas it is not possible to transmit and receive any seismic energy at any frequency from the surface. Producing high output at lower frequencies requires a large reaction mass, which leads to a long heavy tool, which has a negative effect on high frequency output.

Structural and Fatigue Modeling

Raytheon performed structural and fatigue modeling of all of the modules. They investigated the crush resistance and column buckling resistance of the modules when exposed to wellbore pressure. The column buckling increases with decreases in diameter and also goes up dramatically with increases in length. Each of the modules was kept short, partly to increase buckling resistance, and also to help the tool navigate bends in the well.

They examined the joint stiffness and ultimate tensile capability of the individual modules and of the connecting joints to insure that they would withstand the full loads imposed in possible fishing operations, and also the loads in raising this long slender tool from a horizontal to vertical position.

The direct drive servo valve, the actuator, and some other module components go through tens of millions of reversing load cycles. Raytheon calculated the fatigue life of all components and modified them as needed to keep the stresses low enough to give infinite fatigue life.

Dynamic Modeling

Sandia modeled the varying impedance of the reaction mass that would be measured where it connects to the actuator piston as a function of frequency (figure 12) to help in the design of the hydraulic actuator. The impedance changes significantly between 300 and 600 Hz, and then remains relatively flat at 250 lbs. Raytheon incorporated this frequency dependent load into their hydraulic model of the actuator.

Sandia also modeled the transfer function between the actuator force and the clamp force for both the Chevron prototype clamp and the new clamp design (figure 13). This model was used in converting from the acceleration measured on the reaction mass to the force measured at the clamp. Above approximately 550 Hz there is a dramatic reduction in the transfer function and the force measured at the clamp would be significantly less than the force applied at the piston. We compared the model output with the accelerations measured on the reaction mass and the clamp. There is a resonance near 500 Hz where the force output at the clamp due to tool resonances is significantly greater than the force input. These amplitudes were computed using 2% damping, but the actual amplitude of the peak is extremely dependent on the damping term.

Raytheon had modeled the effects of a lighter reaction mass, shorter actuator stroke, and the use of aluminum parts on raising the upper frequency limit of the tool. Their model did not indicate

Modeled Load Impedance Seen By Actuator

Figure 12: Modeled Load Impedance vs. Frequency

Modeled Ratio of Clamp Force to Actuator Force
New Clamp, Team Vibrator

Figure 13: Modeled Ratio of Clamp Force to Actuator Force

much of a benefit from reducing the reaction mass weight, with its corresponding reduction in overall tool length and weight. However, the hydraulic model did not address the overall tool dynamics, and the full benefits from reducing the weight and length of the tool did not show up in Raytheon's models because they did not include the effects of the shorter tool in reducing the tool resonance modes. Sandia modeled the axial vibrator module to determine its resonant modes, and predicted from 18 to 22 resonant modes in the range of 5 to 1500 Hz, with the lowest one at 12 Hz. At these resonant frequencies, much of the energy from the actuator goes into vibrating portions of the tool rather than efficiently generating seismic waves. The main contributors to these modes are the long length of the tool and the fact that it is supported at only one end by a single clamp.

Sandia and Raytheon then both created dynamic models of the source to determine the effects of clamp stiffness and weight, total tool weight, unexcited tool weight, clamp length, and joint stiffness on the tool output bandwidth. They also modeled the force distribution along the length of the clamp, the expected spring rates, and tried to determine whether the clamp and formation stiffness fixed an upper bound on frequency coupled into the formation. The models showed that for a perfectly rigid connection to the wellbore and with no rocking that the tool had a barrel mode at 700 Hz. With the vibrator connected to the wellbore through the clamp this dropped to 400 Hz. The joints between the actuator and the clamp further reduced the overall stiffness. In the initial tests of the axial vibrator module, the clamp adapter offset the centerline of the clamp from the centerline of the actuator, leading to increased rocking of the source.

There was some concern that these off-axis modes might prove destructive, but Chevron's prototype tool is much less rigid than the new tool and had operated successfully for years, which indicated that the deflections due to these modes would be low and nondestructive. A modal test of the axial vibrator module was conducted in January 1994 in conjunction with the initial check-out tests of this module, to determine how much these resonant modes degraded the output. Sandia used the resonances measured during the modal survey to refine their dynamic model.

Wireline Modeling

Some preliminary tests were run on the Conoco cable using Conoco's 4 hp orbital vibrator. When we decided to build a new fiber optic wireline for the source, the wireline electrical and mechanical modeling and design were done by Vector Cable, a subsidiary of Schlumberger. We then had the design reviewed by a wireline design consultant. This is one of the longest, heaviest borehole cables produced.

Tool Design and Fabrication

Overview:

All of the detailed hardware design was done at Raytheon. The electronics were designed by Pelton, Raytheon, and Sandia. Raytheon fabricated the direct drive servo valve in house, but they had most of the other parts machined in outside shops. All of the mechanical assembly and testing was done at Raytheon.

The single axis tool system consists of surface support equipment and control electronics, a special wireline and draw works, cablehead, hydraulic motor/pump module, electronics module, clamp, and axial vibrator module.

The original project included a goal of producing a 3-axes seismic source. It was envisioned that these three different axis vibrators would remain permanently attached to the tool. As we began the detailed design of the tool, it continued to grow in weight, length, complexity, and number of parts. We decided in order to decrease the complexity and the program risk that we would build a tool containing an electronics module and a motor/pump module, which could connect to any one of three separate interchangeable actuator modules, rather than attaching all three actuators permanently to the tool. We included all of the necessary provisions in the present single axis design so that additional vibrator modules can be attached to the tool later. We elected not to fabricate the other two axes until the complete single axis tool had been demonstrated successfully in the field.

The advantages of doing this include having a shorter, lighter, more manageable tool with fewer resonances, higher reliability, lower cost and complexity, lower program risk, and the elimination of a number of transfer tubes, couplings, connectors, valves, filters, etc. A disadvantage is that it may take longer to run the tool through the well three times with individual actuator modules, than one time using all three actuators at each source position, although in many applications not all three axes would be needed.

The axial vibrator module was completed and initial testing conducted in February of 1994. In 1996 the electronics module, motor/pump module, and clamp were completed. In 1997 we conducted overall tool system integration tests, and began geophysical testing.

The original concept design went through a number of additional changes due to technical trade-offs, programmatic changes, financial constraints, and to incorporate additional capabilities. Some of these changes included the following. The positions of the motor/pump module and the electronics module were interchanged in order to ease internal wiring difficulties. The clamp was redesigned from 3 moving shoes to a single moving shoe and an axially preloading hydraulic vise to maintain the high frequency bandwidth. The separate surge chamber used in testing the axial vibrator module was eliminated and the surge chamber cavities were moved into the clamp to shorten the distance between the actuator and the clamp. This also eliminated 3 bolted joints

which would make the tool stiffer and help the high frequency bandwidth. The motor was changed to a high efficiency research motor and the motor/pump module was deleted from the Sandia contract and ordered under a Chevron contract. The electronics changed from dewared electronics with cryogenic cooling and heat sink material to non-dewared high temperature components, with as much of the electronics as possible located at the surface. We added electronic force and phase control. We added fiber-optic telemetry and single-well capability and fabricated a heavy duty fiber optic wireline. Several centralizers and a fishing head were added to the tool.

The temperature of wells increases with depth. The tool was designed to operate continuously at 150 °C and for a short period of time at 200 °C. The present tool was designed to withstand external wellbore hydrostatic pressures of 12,000 psi. The outside diameter of the tool was initially set at 4.56 inch to allow the use of standard size seals, pumps, etc. The axial vibrator module was fabricated at this size. Later, after reviewing tables of casing sizes and drift diameters, it was decided to reduce the diameter of all other modules to 4.40 inch to allow use of the tool in all weights of 5.5" casing.

All of the tool modules contain ports to allow a nitrogen purge of all internal cavities in the field to eliminate the potential for fires or explosions of the internal fluids due to high temperatures, pressures, electricity, etc. All of the cavities that could become pressurized due to hydrostatic pressure have safety plugs that vent the pressure before they are fully removed. And all of the modules have over pressure relief valves.

Because the tool is so long, and needs to negotiate bends in the wellbore, each module was limited to no longer than 12', with flexible joints in-between modules. These joints provided the mechanical attachment to the next module. Hydraulic and electrical lines passed between modules through flexible stainless steel tubes that were flange bolted to each module. The joints also provided a place to break the tool down into easily shipped pieces. The hydraulic lines have check valves at the joints so that hydraulic fluid does not leak when the modules are disconnected. The joints have hard stops that prevent the tool from bending more than 8 degrees to keep from over-stressing the joint when picking the tool up from horizontal to vertical.

The optimum signal from a vibratory seismic source is 2.5 to 3 octaves of the highest frequency seismic waves that will propagate through the formation across the distances needed to the receivers. Beyond about 2.5 to 3 received octaves you reach a point of diminishing returns, where additional bandwidth doesn't improve the wavelet very much. For a given number of octaves, a higher upper frequency gives a much more compact wavelet, which leads to much better resolution. However, high frequencies are attenuated much faster than low frequencies. In addition, formations have highly variable attenuation at different locations and depths. In some locations and over some well separation distances, the maximum frequencies that can be transmitted may be a few hundred Hz, while in other locations it may be a few thousand Hz. Therefore, to optimize the received seismic signal in a given test, the source should be controllable over as broad a range of frequencies as possible.

It is also desirable to have a fairly flat received signal. A received signal that is a narrow spike at one frequency, when cross correlated, gives a broad sine wave, with no way to pick the beginning. A received signal that is flat, when cross correlated, produces a sharp spike, which is excellent for picking arrivals. However, a flat source output does not lead directly to a flat received signal, due to frequency dependent attenuation by the formation. All sources operate somewhere in between the ideal flat output and a narrow single frequency output, and there are always trade-offs. In general it is good to produce a fairly broad, flat output, but under certain conditions it may be desirable to increase the relative amplitude of the high frequency or low frequency signals.

The prototype Chevron tool had a resonance peak of almost 6000 lbs, in a very narrow frequency band. To flatten the output somewhat they hardwired in a notch filter at the resonant frequency of the source to drop this to 3000 lbs. For the new source tool, Pelton provides two methods of flattening the received signal. One of these is to vary the output amplitude throughout the sweep bandwidth. The other method is to use variable dwell to spend more time at frequencies with low output, and less time at frequencies with high output, so that the total received energy is flat across the source bandwidth.

The materials selected for exterior components which would be exposed to well fluids included 15-5 PH stainless steel for the housing, MP35N for the bolts and pins, and 347 austenitic stainless steel. The MP35N and 347 stainless are listed in NACE MR0175-92 as being resistant to H_2S and CO_2 , but 15-5 PH is not. In discussions with Sandia corrosion and materials experts it was determined that 15-5 PH stainless is susceptible to chloride stress corrosion cracking. The chloride levels listed in our requirements under "Typical Well Fluid Composition" were very high. They showed us a piece of austenitic stainless steel pipe similar in corrosion resistance to both the 15-5 PH and the 347 which had been in a dry, high chloride environment for 1 year under no stress and at ambient temperature. It was cracked all the way through in 3 or 4 places, and riddled with pits. They said that at 150 to 200 °C, 10,000 psi, with high stresses, shock, and vibration, that the housing would be attacked very quickly (within a matter of days).

Several alternative housing materials were suggested, including titanium, one of the Hastelloy alloys, or a regular high strength steel with a plated or metal-sprayed coating. We changed the axial vibrator housing material to Inconel 725 which has similar strength to 15-5 and excellent corrosion resistance. We were told that it had similar machining properties to other stainless alloys, but during fabrication of the axial vibrator module, it became apparent that it was much more difficult and much costlier (nearly double the price) to machine than had been expected. It also had significant galling problems. Therefore, the remainder of the modules were made of 15-5, with the understanding that the tool would not be used in highly corrosive wells unless the tool and / or the well were first chemically treated with a corrosion inhibitor.

Figures 14 and 15 show various pieces of hardware being assembled and tested.

A

B

C

D

E

F

A) Cemented Well Casing Test Fixture in Laboratory

B) Hydraulic Filter Module

C) Electronics Module

D) Cablehead

E) Vertical Vibrator Module
in Model Test Fixture

F) Joint with transfer tubes

Figure 14: Hardware Photographs

A) Terminating Source Cable
 B) Direct Drive Servo Valve
 C) Centralizer
 D) Exxon Seismic Receiver Sonde

E) Flex Joint
 F) Clamp
 G) Vertical Vibrator, Surge chamber,
 and Chevron Clamp

Figure: 15 Hardware Photographs

Cable Head

The cablehead was designed and fabricated by Raytheon, and included ideas from Conoco's cablehead. The cablehead connects the 20,000' fiber optic wireline to the source tool. The cablehead included a centralizer to help orient the source tool in the well. The cablehead also provides a clean breakaway from the cable and a fishing head compatible with standard fishing tools in case the tool became stuck in the well. To accomplish this, the cablehead includes an engineered in strength member which fails predictably at a given load, rather than relying on the cable armor to break. It was designed to release at 11,000 lb to 12,000 lb. The wireline was terminated in the cablehead and a pull test to destruction was performed at Raytheon to verify that the cable separated cleanly from the cablehead leaving a clean surface to fish the tool if necessary. The test was successful. The cablehead also includes free space, an optical fiber, and electrical wires which are intended for inclusion in the future of a fiber optic gyro to provide continuous source tool azimuth information to the surface.

Motor/Pump Module

In the original design, the motor/pump module was located below the electronics module. During detail design Raytheon decided to locate the hydraulic module above the electronics module in order to minimize the number of wires that had to pass through the motor/pump assembly. This kept many of the low-level sensor and control lines in the electronics module away from the high power AC signals driving the electric motor, and simplified the connectors and motor/pump module. However, it required that hot hydraulic lines from the motor/pump module pass through the electronics module to the axial vibrator module. In order to minimize heat transfer from these lines into the electronics module, the hydraulic lines were double walled with a dead air space in-between.

The motor/pump module contains an MTI high performance electric motor directly coupled to a Vickers hydraulic pump. The outside of the motor and pump are immersed in the Tegra C hydraulic fluid used to operate the actuator in order to maximize heat transfer from the motor and pump to the outside wall of the module. In addition, a reduced pressure by-pass valve continuously circulates fluid through the motor to help carry away heat. The module also contains a hydraulic oil reservoir which is gas charged and supply pressure pre-loaded on the return pressure side to maintain positive pressure at the pump inlet. The reservoir is sized to allow for fluid expansion over the operating temperature range of the tool. A filter module contains high pressure supply side oil particle filters and low pressure pump intake side particle filters and magnetic filters. These filters are critical, since the hydraulic fluid flows over the outside and through the inside of the motor and pump. The filters can be easily changed in the field without disassembling the module. The module has pressure, temperature, and reservoir fluid level transducers that provide diagnostic information to the surface. It contains an over-pressure relief valve for safety. The fill plugs vent system pressure before they are fully removed as a safety feature. All of the free volume in this module and all of the other modules is purged with inert nitrogen gas to eliminate the possibility of a fire or explosion. The system contains a downhole hydraulic by-pass valve controlled by the Pelton electronics which prevents the

hydraulic actuators from operating before both the Pelton and Raytheon electronics perform self tests and status checks. The motor and pump are contained inside a steel pressure vessel, and the overall motor/pump module is 4.40" OD.

Motor

Los Alamos had worked in the 1980's on high temperature electric motors for use in electric submersible oil well pumps. They had managed to adapt a commercial downhole oil pump motor to work continuously under load in a wellbore at 200 °C for a year without failing. We had originally planned on using a modified version of these 60 Hz three phase AC motors to power the downhole hydraulic pump. However, a thermal analysis of the overall system showed a significant heating problem due to the large amount of power needed downhole. After visiting the manufacturers we decided that these pumps would not work for our application. They generate significant amounts of heat and rely on continuous fluid flow of the well fluids being pumped past the motor housing to keep them cool enough to survive. Since there would be no movement of the well fluids in our application aside from natural convection, these motors could not be used. These motors also had to be pressure balanced to the outside wellbore pressure, or would have to be small enough diameter to fit within the pressure housing of our tool.

There was also a problem with the speed of standard AC motors. They run at 3600 rpm due to the available power. At this speed the pump would not produce the flow required. We discussed gearing up the speed of the output shaft of the motor to 7200 rpm or higher. We also discussed using a commercial uphole inverter to operate at a higher speed, using a reluctance motor rather than an induction motor to keep the heating in the stator rather than the rotor, removing the pressure compensating oil bath and just running the motor very hot, and using other types of wire including mica insulated wire, improving the motor efficiency by adjusting the power factor uphole, and using a controlled soft start to avoid power surges at start-up. Some suppliers said that we would not be able to perform power factor correction uphole because of the inductance of the long wireline which changes continuously as the cable is unreeled, and that we couldn't do power factor correction downhole because the electronics required can't withstand the 200 °C requirement.

Raytheon solicited quotes from a number of motor manufacturers, and received many innovative responses. In the end Raytheon selected Montevideo Technology, Inc. (MTI), who had built advanced high efficiency research motors for use in all-electric vehicles. MTI proposed a Digital-Signal-Processor-based Advanced Synchronous Permanent Magnet AC Motor and controller. MTI's motor has a capability to develop reactive power to the wireline as needed to compensate for changing load conditions. They use over excitation of a permanent magnet synchronous AC motor with extra magnets on the rotor which causes a back EMF higher than the line voltage. An uphole controller monitors the phase lag under various load conditions and continuously adjusts the phase of the uphole drive signal, changing the relative angle of the rotor at switching time, adjusting how much reactive power is generated. This results in a much more efficient motor (91%, compared to conventional AC induction motors at ~ 80%), which in turn helps to alleviate the thermal problems. It also reduces wireline cable losses.

The motor design length was originally 48" long. MTI had built similar motors in the past, but had not wound a 48" long motor before, made a 1000 V controller, or used over-excitation on a long cable. MTI did an optimization on the design and reduced the length to 24", with lower losses. This made the motor easier to build, but it still required special coil winding equipment. The motor is immersed in hydraulic fluid and also has hydraulic fluid circulated through it in order to carry away heat. It uses covered permanent magnets with an Inconel wrap to hold the magnets in place. The motor has a full load rated speed of 8100 RPM, but can operate at any user selected speed between 1700 and 9200 RPM. The windings are rated at 250 °C, and the motor is rated at 11 kW. The permanent magnets are rated at 300 °C. The magnets are skewed to reduce cogging. They shrink fit the housing onto the stator for good thermal conductivity. MTI did thermal modeling of all of the losses in the motor. The total heat generated at maximum power is 800 watts. They have test data showing that they need less than 2 gpm of oil flow through the motor to dissipate the heat. While the motor is designed to operate on the GRI cable, it can be modified to run on any other cable with only a software modification to the controller.

The surface support equipment for the motor includes a three phase power amplifier to drive the downhole motor, a motor controller, and a PC based graphical user interface. The uphole controller for the MTI motor uses digital signal processing vector control technology to perform real-time power factor optimization and energy use optimization under partial loads. The controller maintains the power factor at 0.99. The PC based user control interface continually displays motor status and allows modifications in motor operating conditions. It has a variable start-up ramp rate and variable motor speed. It displays motor speed, motor temperature, input and output frequency, voltage, current, power, and power factor. It also includes threshold levels, warning messages, short circuit and over-voltage protection, and automatic shut down. The controller uses sensorless position loop closure to monitor the position of the rotor. It monitors the current on each of the wires from the three phase power amplifier output and the voltage difference between these lines, and then calculates the rotor position. This is used as the feedback signal to control the pulse width modulation.

A synthetic wireline with the same electrical characteristics as the 20,000' wireline was fabricated by Raytheon to aid MTI in their motor drive optimization. After the motor was designed and built it was tested with the synthetic wireline to conduct loop closure tests, transient response, cold start tests, speed torque tests, and efficiency tests. The overall motor efficiency was 91%, and the motor had a temperature rise of only 28 °C when operated in air at full load. This is especially important for operation in hot wells. The decision to use this motor resulted in a significant delay in the program schedule and increased costs, but it was felt that the improvement in performance was worth it. The motor was then shipped to Raytheon for attachment to the pump and assembled into the motor/pump module housing. MTI delivered 2 motors, 2 controllers, and 2 interface boxes, so there is a spare of each item.

Pump

Raytheon had planned on using a variable pressure, variable flow pump to control the force output vs. frequency. Pelton determined that it would be much easier to control the force

electronically using a force feedback control loop, with accelerometers on the reaction mass and clamp providing the feedback signal. They recommended using a constant pressure, variable displacement pump to supply the actuator, and adjusting the force on the actuator by changing the pulse width modulation and the lead of the drive signal to the direct drive servo valve. Pelton had done this in the past with surface vibrators using accelerometers on the reaction mass and on the base plate to provide the input signals for automatic gain control. We agreed to use a 5000 psi fixed pressure, variable flow pump, with a maximum continuous output of 3.5 gpm.

A contract was placed with Vickers for the hydraulic pump. This division of Vickers designs hydraulic systems for commercial and military aircraft, jet engines, military vehicles, and shipboard applications. The pump is based on an existing Vickers pump used in aircraft auxiliary power units. It displacement was modified to 0.18 cubic inch, and designed for operation at 7200 RPM, average output of 3.5 gpm, and a peak flow of 5.5 gpm. The pump is 9.5" long x 3.36" in diameter. The measured pump efficiency was 88%. Chevron Tegra C hydraulic fluid was selected for use in the actuators because of its high bulk modulus and high temperature capability. It is highly viscous at room temperature. To reduce the risk of cavitation at the pump inlet the reservoir maintains a positive inlet pressure. When the tool is started it is started with a slow ramp up in speed. Once the pump operates for a short time there is enough internal heating to keep the viscosity of the fluid down so that the fluid will flow into the pump. All of the materials used in the pump were tested for compatibility with Tegra C fluid at 150 °C for 10 hours. There were no material compatibility problems. During load testing the temperature differential inside the pump relative to the inlet fluid temperature varied from 20 to 30 °C.

Electronics Module

The electronics module performs a number of power, control, diagnostic, and communications functions, and contains electronics designed by Raytheon, Pelton, and Sandia. The circuit boards are mounted on both sides of a central aluminum heat sink/ support rail which runs the length of the electronics module. The outer pressure housing of the electronics module is 4.40" diameter. The module has centralizing springs and quick disconnects at both ends. The housing is filled with Dow Corning 550 silicone thermal conduction fluid to maximize heat transfer from the electronics to the outside of the tool. The motor/pump module was placed above the electronics module so that the high voltage high current AC lines supplying the electric motor would not have to pass through the module containing the sensitive electronics. This required that the hot hydraulic fluid from the motor/pump module be piped through the electronics module to the actuator. To minimize the heat transfer from these pipes into the electronics module Raytheon used double walled pipes with dead air space in between. The module has pressure bulkheads at each end and multi-pin connectors that include electrical, coax, and fiber optic pins. All of the mechanical portions of the module were designed and fabricated by Raytheon.

The electronics module includes the following: a downhole regulated power supply to provide a number of voltages to all of the electronics, a switch mode power supply that drives the electric coils in the direct drive servo valve, a valve and actuator control loop section that monitors and controls the position and velocity of the servo valve and the hydraulic actuator, an instrumentation board that receives inputs from all of the diagnostic transducers in the tool, a section which

generates vibrator sweep signals and provides control functions, and a telemetry section that converts the electrical signals to optical signals for transmission over the wireline.

Pelton Electronics

Pelton builds commercial sweep generator, control, communication, and diagnostic electronics for surface vibrators. The team had planned on using essentially Pelton's existing electronics, making a few upgrades, and packaging it all to go downhole. Pelton's existing electronics were designed to control surface vibrators which usually operate from approximately 5 to 70 Hz, so Pelton had designed their electronics to operate at frequencies up to 500 Hz at ambient conditions. This borehole application required both higher speeds and much higher temperature operation. For our application the electronics were redesigned to operate at frequencies up to 2000 Hz. The servo valve in the tool is fast enough to try to follow 500 Hz electronics updates in a step-wise fashion, rather than producing a smooth sinusoidal sweep, which in turn increases the distortion in the wave forms at higher frequencies. The existing Pelton electronics contained 5 microprocessors and batteries which were not rated for high temperature operation. At high temperatures the internal delay times also increased. Pelton felt that they could package their electronics to work downhole, but not at high speed at high temperature.

An alternative to putting all of the electronics downhole was to leave most of it at the surface and communicate at high data rates between the surface and the tool. Doing that would require communicating at 1 Mbit/sec over 20,000' on a noisy wireline. Sandia had experience in fiber optic transmission for downhole tools, based on earlier work on a multi-level seismic receiver. They investigated the possibility of leaving most of Pelton's electronics uphole and communicating with a minimal amount of electronics in the tool over a fiber optic link. This approach would minimize the number of high temperature components that had to be found, solve the high speed operation problem at high temperature, keep most of the electronics uphole which allows easier troubleshooting and higher reliability, and eliminate the need for high temperature batteries. In addition, the data rate over fiber optics is high enough that you can send raw data to the surface and do digital filtering there, eliminating the need for downhole digital filters.

In addition to the advantages of fiber optics to the Pelton electronics, the team had decided to include provisions for single-well applications of the tool. In these applications, a receiver array is hung below the source in the same well, and the receiver signals must pass through the high power AC noise in the motor/pump module and alongside the high power AC lines over the full length of the 20,000' wireline. Using fiber optics for these signals would eliminate concerns about induced voltages on the receiver data lines. In addition, fiber optics accommodates the very high data rates needed to transmit data from an array of receivers and eliminates the constraints of downhole memory in the receivers. Several of the team companies also wanted to be able to operate the source in deeper wells than the 10,000' length of the Conoco wireline.

As a result, a decision was made to build a new fiber optic wireline and to keep as much of the Pelton electronics as possible at the surface. GRI funded and Chevron contracted for the wireline and draw works. Sandia designed and fabricated the fiber optic telemetry system and tested it for

high temperature operation. Pelton was able to operate their remaining electronics that had to go downhole, including their digitizers, Hitachi microprocessor, and memory chips to 200 °C.

Pelton's electronics consist of:

1. Pilot sweep generator module which can generate drive signals with variable sweep speed, amplitude, dwell, and upper and lower frequencies limits. The various sweep patterns are computed and generated by the uphole electronics and transmitted downhole to the direct drive servo valve driver in real time. The uphole electronics can store up to 16 different sweep patterns, totaling 64 seconds of sweep time. The sweep signal is a ± 10 Volt signal with 16 bit phase and 16 bit amplitude and a sample rate of 1/4 msec.
2. Servo Status module that displays diagnostic information from the transducers in the tool. These include actuator position, scan initiation time, clamp position, pressures (hydraulic supply, return, electronics module, external well pressure), reaction mass acceleration, force signal, and temperatures (motor, pump, electronics, hydraulic fluid, torque motor, ambient). The downhole electronics transmits three 16 bit signals to the surface at 1/4th msec sample rate, and transmits 16 other signals at a 4 msec sample rate. Raytheon sends scaled, filtered signals to the Pelton electronics from all of the diagnostic transducer except for the four accelerometer signals which are raw signals. Pelton digitizes the signals using analog filters and A/D converters and sends them to the surface. A manual reset over-ride feature monitors the voltage on a pair of lines and reset and un-clamp commands at the tool if the voltage drops below a set threshold level.
3. Communications module for sending and receiving commands between the uphole and downhole electronics. It also sends data between the receiver truck and the source truck over a surface fiber optic line.
4. Phase and amplitude control module at surface, which computes the vibrator output signal in real time from the incoming downhole accelerometer data, compares the vibrator output to the reference sweep, and minimizes the difference by generating a compensated analog vibrator drive signal in real time. This module can also perform force level control to flatten the force output, or dwell control to flatten the energy by spending more time at frequencies where the source has low output.
5. The uphole source control electronics receives a time break and a start signal from the seismic recording system to start the sweep. The system also outputs the reference source drive signal to the seismic recorder for use in later processing.

Figure 16 describes the Pelton control electronics. Figure 17 shows a wiring diagram and sensor description for the motor/pump module and for the electronics module.

Pelton recorded accelerometer outputs from the first test of the axial vibrator module to aid in their design of the force feedback loops and other control features. Pelton found that they could modify their existing Advance II electronics to meet our requirements rather than designing all new uphole electronics. The Pelton "Advance 2 Vibration Control Electronics" goes downhole.

Control Electronics for Downhole Hydraulic Vibrator

Figure 16: Pelton Control Electronics

The "Advance 2 Encode Sweep generator", a PC and a "VibQC" diagnostic display are all located in the control trailer at the surface. They built and tested low temperature versions of their boards, and used them in early lab tests of the axial vibrator module. Later they built high temperature versions for use in the downhole electronics module. Pelton interfaced their boards with the Sandia fiber optic telemetry boards and all of the Raytheon diagnostic inputs and controls.

Figure 18 shows the output force vs. frequency for the team tool when operated open loop (top) and closed loop (bottom). In the open loop test the source was operated at fixed 100%, 25%, 6%, and 4% drive levels. Due to tool resonances, actuator limitations, etc. the output force is not flat vs. frequency at any of these levels. In the closed loop test, the electronics reduce the drive at the tool resonances and increase it to a maximum frequencies with low output. The result is a much flatter force vs. frequency output. The electronics can not get higher output from the tool than it produced at 100% drive in open loop mode, but in closed loop mode it can make the output much more uniform across the frequency spectrum.

Figure 19 shows the output energy vs. frequency when using a linear sweep compared to using a compensated non-linear sweep. With a linear sweep the total energy output is a maximum at the tool resonances, and then droops off with frequency. Pelton recorded that output, and generated a compensated non-linear sweep that dwells longer at frequencies with low energy output and passes quickly through frequencies with high energy output. As can be seen in the plot, the resulting energy vs. frequency output from the tool when driven with this non-linear time dwell compensated sweep is very flat over the full bandwidth of the tool. This technique had been used successfully by Pelton in the past in controlling surface vibrators.

The team tested the combined downhole and uphole electronics over short fiber optic cables, and then over the 20,000' wireline, with and without the motor/pump module powered up. The electronics have now been used in several field surveys and provide excellent tool control and diagnostics.

Figure 18: Pelton Variable Amplitude Drive to Flatten Force Output

a) Open Loop

b) Closed Loop

Controlling Output of Hydraulic Vibrator

Figure 19: Pelton Variable Dwell Producing Flat Energy vs. Frequency Output

Fiber Optics

Several possible implementations of fiber optic telemetry were investigated, including using two dedicated fibers, a single fiber in a time shared mode, or a single fiber with two optical frequencies. With two optical frequencies, one of the frequencies has considerably higher optical loss in the fiber than the other. A time shared implementation requires electronics for handshaking. We decided the most straightforward method, which required the least number of high temperature components and allowed continuous two-way communication, was to use two dedicated fibers, one for transmitting down to the tool, and one for transmitting from the tool up to the surface (Franco and Morgan 1997).

There are a number of trade-offs between single mode or multimode fiber, including optical attenuation, signal bandwidth, connector insertion loss, mechanical stresses, coupling loss to the LED or photodiode, changes due to temperature and stress, etc. Single mode fibers typically use laser diodes rather than LED's because of their smaller acceptance angle, but laser diodes fail catastrophically at high temperatures and often require thermoelectric cooling. We decided to use multi-mode fibers for the communications link. Single mode fibers were included for future use with fiber optic gyros in the source and the receiver.

The telemetry system was based on earlier work with the OYO/ Sandia 5 level receiver array. A block diagram of the system is shown in Figure 20. Two identical systems were used, one for the downlink, and one for the uplink. LED's typically have higher operational temperature limits than photodiodes. Sandia selected and tested several LED's and photodiodes at high temperature. The final parts used were from Litton. The LED's operated satisfactorily to 200 °C, but the photodiodes failed above 175 °C. Later analysis by Litton showed this to be an optical failure due to reflow of residual low temperature solder and low temperature epoxy at the receiver/fiber interface. In the future Litton will build these parts using higher temperature materials. These versions of high temperature LED's and Photodiodes will be offered commercially by Litton.

The mechanical portions of the seismic tool are rated to 200 °C, but the present wireline is only rated to 150 °C, so the fiber optic telemetry systems limit of 175 °C is adequate at present. Additional development would likely raise the temperature limit of the photodiodes to 200 °C.

The fiber optic transmitter and receiver that we are using are capable of data rates of 20 Mb/sec. They were selected for this high temperature application because they use CMOS TTL technology which is inherently tolerant of higher temperature, and also because of their low self heating. The fibers themselves can accommodate 50 Mb/sec rates. However, there are other speed constraints. The source commands and source status signals are transmitted into a continuous data stream using Manchester encoding. This limits the downlink data rate to ~ 2 Mb/sec. We decided to operate at 1 Mb/sec to accommodate the speed of the downhole processors Pelton was using. The telemetry system takes into account the 30 microsecond delay for the optical signals to travel the length of the wireline.

The complete fiber optic telemetry system, including the uphole and downhole electronics boards, LED's, photodiodes, connectors, and short fiber optic jumpers was tested in an oven, with a

Figure 20: Fiber Optic Telemetry System

variable optical attenuator simulating wireline losses, to determine the link margin. There was ample link margin to operate at 1 Mb/sec on the Downlink and 5 Mb/sec on the Uplink up to 175 °C. The telemetry system was also tested with the Pelton uphole and downhole electronics. A variable optical attenuator set at 14 dBm attenuation was used to simulate the wireline and connector losses in each fiber. Pelton successfully transmitted signals over the fiber link with this attenuation. Signals were transmitted at 1 Mb/sec on the downlink and 5 Mb/sec on the uplink with zero bit rate errors. When the wireline, connectors, and slip rings were completed, the actual optical losses were much lower than the 14 dBm used in the test.

High Temperature Electronics

In order to meet the 200 °C temperature requirement, we investigated putting the electronics in a vacuum insulated dewar with phase change heat sink material, but with so much heat generated by the power supplies and motor driver this was not feasible. We also considered using downhole refrigerators or using thermoelectric coolers on specific sensitive items like the microprocessors. In the end we decided to not use any active or passive cooling, but rather to use as many high temperature rated components as possible, to immerse the electronics in fluid to improve the heat transfer out of the electronics module, and to put as much of the electronics uphole as possible and communicate over fiber optics with the downhole electronics.

The team compiled lists of electronics components that had been used in other downhole tools at high temperature. These were not guaranteed to 200 °C but have been used in similar applications. Many of the components that Pelton and Raytheon needed were on the list. Some 125 °C rated components were used, but were tested to higher temperatures. Raytheon located 200 °C versions of all of the components they needed for their portion of the electronics. Most of the analog devices and digital logic components used were commercial CMOS parts in metal or ceramic packages. CMOS is inherently more tolerant of high temperature operation, and can operate up to 200 °C, as compared to Bipolar technology which fails at 125 °C. Operational amplifiers, analog multiplexers, and MOSFET discrete components with isolated gate inputs all worked well to 200 °C, as did ceramic capacitors, metal film resistors, and silicone diodes.

High temperature boards with copper on polyimide glass were used, and the components were inserted using high temperature solder. A sample functional electronics board containing one of each electrical component planned for the electronics module was fabricated. It included some parts tinned with low temperature solder but soldered into the board using high temperature solder. Raytheon tested the board for 30 days at 200 °C while monitoring the electrical functionality of the board, without any failures.

Clamp

One of the major concerns with any type of clamped downhole tool is that in the event of a power failure, mechanical malfunction, or at restrictions in the well the tool may become stuck. It is absolutely imperative that the clamp have a fail-safe retraction mode. To ensure fail-safe retraction, this clamp includes redundant normally-open electrically operated bypass valves to relieve the pressure from the clamp pistons in the event of a power failure. The electronics has a panic mode circuit which un-clamps the tool and resets the microprocessors if the voltage drops

below a threshold. The clamp also has spring return force to collapse the clamp shoes in the event of a hydraulic failure. And the valve spool on the clamp is spring biased open.

The clamp must be extremely stiff in order to transmit the high frequency forces from the actuator to the well casing. The initial clamp design included three moving shoes to keep the source tool centered in the well regardless of the well diameter, which would eliminate the tendency for the source to rock in the well. However, we were concerned about the stiffness of that design, so we selected a design with two fixed shoes and one moving shoe. The moving shoe is pressed out against the well casing by hydraulic cylinders, which are pressure balanced to wellbore pressure so that the clamp does not have to overcome increased resistance with well depth. After the clamp shoe contacts the wall then an axial hydraulic cylinder forces the edge of the clamp shoe down against the tool body, eliminating all clearances. This provides an extremely stiff clamp.

Oil wells have a layer of cement between the casing and the formation. This cement forms a fairly weak bond to the casing, so the clamp must distribute the holding force over a large area in order to not destroy the casing cement bond. Raytheon modeled the shear stress at the casing/cement interface due to clamping. The clamp could induce a peak shear stress of ~170 psi, which is above the cement bond strength listed in cementing literature. Several team members stated that this would be very localized, and that formation pressure would help seal any localized damage. The shear strength of the cement-casing bond will also increase in proportion to the clamp force of the vibrator due to the induced normal stress. Bjorn Paulsson said that the Chevron Prototype clamp puts similar stresses on the casing, but that he had not seen any damage when he has run comparative cement bond logs before and after using the prototype tool. If there is any damage, it is too small to detect.

There are also concerns about clamping into old weak casing. This clamp includes an LVDT to monitor the position of the clamp shoes. A cut out is tripped if the clamp tries to push the clamp shoes beyond the known diameter of the well casing, or if the wireline operator tries to move the source while the clamp is extended.

Our initial tests of the axial vibrator module with the old prototype Chevron clamp indicated that with a heavy tool, much of the reaction force generated by the hydraulic actuator and reaction mass is used in shaking the rest of the tool, rather than being transmitted to the formation. Following this initial test the weight of the modules, including the clamp, was reduced as much as possible. In addition, Raytheon designed a hydraulic vibration isolator system that allowed the clamp to "float" on a hydraulic cushion attached to the rest of the tool modules above the clamp. This essentially decoupled the cablehead, motor/pump module, and electronics module portion of the tool from the clamp and axial vibrator, effectively removing the contribution of their weight and length from the resonances of the tool as seen at the clamp, and also minimizing vibration loads on the electronics and motor/pump modules.

We also minimized the distance and the number of joints between the reaction mass and the clamp. In the original hardware we had included a surge chamber section between the axial vibrator actuator and the clamp to minimize the amount of "water hammer" when the direct drive servo valve switched at high frequency. In the new clamp, we eliminated this separate surge

chamber and incorporated the surge chamber volumes into unused areas in the clamp. The clamp is 4.68" in diameter. Different size fixed shoes can be attached to it to adapt it to various casing sizes.

Axial Vibrator

The axial vibrator contains a high performance direct drive servo valve, which operates a linear hydraulic actuator. The actuator is attached to a 250 lb tungsten reaction mass. It is also attached to the axial vibrator module pressure housing, which in turn is attached to the clamp. When the actuator shakes the reaction mass, an equal and opposite force is imparted to the actuator, and in turn to the module housing, clamp, well casing and formation, generating seismic waves in the formation.

Figure 21 shows the axial vibrator module hardware, along with the surge chamber and Chevron clamp used in early tests.

The reaction mass is balanced vertically at the center of the actuator stroke by means of differential areas on the actuator piston. Belleville spring stops prevent the reaction mass from bottoming out at either end of its travel. A splined shaft mounted to the reaction mass at the opposite end from the actuator keeps the reaction mass from rotating. The direct drive valve, actuator, and reaction mass are contained in a pressure housing to protect it from the wellbore pressure and fluids. Since the source is clamped in place and does not change its volume while shaking it generates very little tube wave energy.

There are two accelerometers mounted on the reaction mass and two on the clamp. The signals from these are used by the Pelton electronics to control the drive signal to the actuator in order to produce a flatter output over a wide frequency range. They are also used in a diagnostic mode to evaluate the health of the tool and to detect clamp slippage.

The direct drive servo valve was based on earlier high performance valves that Raytheon had made for aerospace and active vibration damping applications. Raytheon put a much more powerful electric motor on this valve and optimized the valve motor and switch mode driver for high frequency response. The valve motor is a high temperature brushless DC motor with samarium cobalt magnets. The quiescent leakage of the valve is less than 0.02 gallons per minute, to minimize flow requirements and excess heat generation. In bench top tests to determine its upper frequency limit, the new direct drive servo valve produced 10% stroke out to 1000 Hz, and still had detectable motion to 1500 Hz, as compared to previous servovalves which have an upper frequency limit of approximately 700 Hz.

Axial Vibrator Module Functional Test

After the Axial Vibrator Module was completed, it was initially tested at Raytheon in a simulated well casing in 55 gallon drums filled with cement (see Figure 14). It was operated at full power with an input drive signal from 0 to 1400 Hz at 3000 psi system pressure from a hydraulic test

Figure 21: Axial Vibrator Module

stand (reduced from 5000 psi due to hose ratings). In all of the tests at Raytheon, they recorded the drive signal and the output from accelerometers on the reaction mass, clamp, and casing. These laboratory tests were useful for comparing output from test to test, but do not translate directly to the signals that would be measured by a seismic receiver if the source tool were in a well.

The tool operated successfully in a number of tests spanning several months. In one test the actuator bore and piston were damaged. Raytheon believes this was due to localized heating and expansion of the piston within the bore, resulting in seizing. This could have been due to a particle in the fluid or to too close a fit between the piston and bore so that there was piston-on-bore rubbing rather than piston-on-seal rubbing. The parts were successfully reworked by grinding, plating them up in size, and regrinding both parts to a known fit with looser clearances. The module was re-tested and operated successfully.

In February 1994, the axial vibrator module was shipped to Chevron's La Habra test facility for a series of tests including modal testing to determine the tool's resonances, functional testing to insure it would operate reliably over millions of cycles, and seismic tests to compare its output directly with the Chevron prototype source.

Modal tests were conducted on the axial vibrator to determine the tool's resonance's to aid in designing the clamp and joints. The modal tests were conducted by Rush Allen of Rush Engineering. A number of accelerometers were attached along the length of the axial vibrator, to the reaction mass, the clamp, and the test fixture, in order to determine tool resonant modes, the amount of energy generated by the vibrator, and the relative amount of energy transferred by the clamp to the test fixture at each frequency. An initial free-free modal test of the Sv module was conducted. The hydraulics were not powered, and the module was suspended horizontally on foam blocks. From this they determined tool damping to be 1% to 2%. The second test was a fixed-free test with the actuator suspended vertically, clamped into a piece of well casing cemented into a 3500 pound test fixture slung from a crane (see Figure 14). The hydraulics were powered up but the actuator was not moving. The tool was rung with a calibrated hammer and the response from the accelerometers recorded. The third test was a fixed-free test in the concrete fixture with the hydraulics powered up and operating the actuator. The source was operated at 4000 psi and was swept from 20 to 1000 Hz. There was a mode at 60 Hz due to the tool being off-center relative to the clamp. There was a variable mode around 140 to 210 Hz that is oil column dependent. This is where the peak output will occur. The modal tests indicated poor source output above 600 Hz and that little of the seismic energy from the source was coupling through the clamp into the test fixture above ~ 400 Hz. It was felt that some of this was due to being coupled to an offset clamp through an adapter plate. The offset between the clamp and vibrator axis caused considerable tool rocking, which would tend to couple more energy into off-axis bending modes. The new clamp design aligned the clamp and vibrator axis.

The tool was then tested in a borehole at Chevron's La Habra test site, for comparison with Chevron's prototype hydraulic vibrator. The module was mounted to an existing clamp from the Chevron prototype source using a clamp adapter. The axial vibrator was clamped in place at a depth of 100' and a common source fan was collected using Exxon's receiver array located in a

second well 400' away. The vibrator was powered using surface hydraulics, a breadboard version of the driver electronics, and a fully programmable sweep generator. Pelton recorded accelerometer outputs from the module to help in the design of the force feedback loops and other control features. Pelton indicated that the harmonic distortion with our tool looked very good compared to surface vibrators.

Pelton operated their sweep generator at full force, so they can only decrease the drive signal to flatten the curve, and control the dwell to modify the total energy into the formation. They saw no problems with controlling the phase but were concerned about the low amplitude output. They normally use the weighted sum of the reaction mass and base plate accelerometer signals for force control. The reason for using force control in surface vibrators is to prevent decoupling and to give a level output. Pelton said there are two camps of thought-- one says you should have a flat force output vs. frequency, the other, which they favor, is that you should have maximum output vs. frequency. With phase control you make the phase of the weighted sum the same as the phase of the drive signal.

The module was operated for four days, representing tens of millions of valve and actuator cycles, with no problems. Following the test the module was disassembled and inspected, and showed no damage.

The seismic data was recorded using Exxon's 5 level clamped receiver string. The sweeps were linear 7 second sweeps from 10 to 640 Hz at full power with the source clamped in the borehole. The raw uncorrelated signals from the new source were significantly stronger than those from the Chevron prototype. However, the output force vs. frequency was not nearly as flat or broad as the hydraulic modeling had predicted, and the signals from the new source did not show as much improvement following correlation as the signals from the prototype source. It was felt that the narrow frequency range of high source output might account for the ringing in the seismic data.

There were a number of possible explanations for the output not being as broad or high frequency as initially modeled, and for the less than expected improvement following correlation. All of these were investigated, modeled, and tested in the lab. It turned out that a number of factors contributed to the lower than modeled output. Some of these are discussed below. This investigation and testing into ways of improving the high frequency output resulted in improved source output, and was extremely useful in planning for future hardware modules.

Dynamic modeling showed a fairly abrupt phase shift of 180° in the output of the tool at most of the tool resonance modes, which could account for the poor correlation with the electronic drive sweep. The tool resonances are a function of the 4th power of the tool length. Since Chevron's prototype tool was so much shorter than the new tool, even though it was not nearly as stiff it may not have as many modes, which might explain why the data from the Chevron tool improved a lot after correlation but the data from the new tool did not. Sandia modelers felt that most of the problem was due to the length of the tool, and that a new clamp would not improve the output. This led to Raytheon designing a hydraulic isolator into the new clamp to decouple most of the rest of the tool from the vibrator module.

Paulsson had seen harmonic distortion on his prototype source at low clamp pressures which improved when he increased the clamp pressure. He felt the low output force vs. frequency and the harmonic distortion might both be due to clamp slippage. The prototype clamp was only designed for a maximum source output of 3,000 pounds force, and the new source was putting out over twice that. If the clamp slipped the output at the clamp would no longer look sinusoidal and could account for the poor correlation. In earlier tests with the Chevron tool without the hardpoints and at 1500 psi they saw clamp slippage, but in our tests the accelerometers didn't indicate any clamp slippage. We found during later disassembly and inspection that part of the bandwidth and force limitation was due to problems with the Chevron clamp. The clamp has a number of threaded-in pointed nubs that contact the well casing. These had experienced fretting wear and were loose, resulting in filtering out high frequency vibrations. These were replaced with new, pressed in nubs, and the tool output showed a marked improvement in output for all frequencies from 150 to 600 Hz.

Raytheon felt that part of the problem was due to oil column/ tool weight resonances which had not been properly accounted for in the model. They modified their model to include the oil column resonance and the results were much closer to our test results. The actuator had been designed with a maximum stroke of 0.50", which was needed to achieve high force output at low frequencies, since the force is proportional to acceleration which is proportional to stroke length. However, this gives a fairly large volume of oil behind the actuator, which is softer than a smaller volume. They modeled the effects of decreasing the stroke from 0.50" to 0.10", which increases the stiffness and hence the resonant frequency of the system, reducing the low frequency output but raising the high frequency output.

The servo-valve drive electronics that were used in this test were an early breadboard version, and did not have as much power as the final design. Raytheon tested the team tool in the lab using 25%, 50%, and 100% power on the valve drive (figure 22). The 100% power on the valve drive gave a much higher tool output. Raytheon re-designed their power section to increase its output and insure that the drive electronics would not be a limitation.

Chevron had results from a test of their prototype tool in 1985 in which two different reaction masses were tested using the same actuator and clamp. The reaction masses were 75 lbs and 25 lbs. The 25 lb reaction mass had a natural frequency of 250 Hz and the 75 lb reaction mass had a natural frequency of 100 Hz. Raytheon modeled the effect of reducing the reaction mass from 250 lbs to 100 or 50 lbs in order to reduce both the length and the weight of the tool and increase the tool resonant frequencies. Raytheon re-tested the team tool in January, 1995 with a 50 lb reaction mass and with a 250 lb reaction mass. Figure 23 shows the output from the team tool using a 250 lb reaction mass and using a 50 lb reaction mass. In both cases the tool used aluminum parts. Since these two tests were conducted at the same time with the same clamp, they are a valid comparison. However, the results cannot be compared directly to later tests because these were done using the Chevron prototype clamp, which had loose nubs.

Effect of Command Force Level

Team Tool, 5000 psi, 50 lbs. mass

Values from mass accelerometer

Figure 22: Effect of Command Force Level on Force Output

Effect of Reaction Mass Weight

Values from Reaction Mass Accelerometer

Figure 23: Effect of Reaction Mass Weight

Raytheon speculated that there may have been air in the hydraulic oil which would dramatically reduce its bulk modulus. Raytheon modeled the effect of ½, 1, and 2% air entrained in the oil. The model showed a dramatic drop off in high frequency output. 1% air entrainment cut the bulk modulus of the fluid in half. Raytheon later tested this theory by de-aerating the hydraulic fluid under vacuum and heat for a number of days before re-running a test. However, there was no appreciable difference in the output following de-aerating the oil, indicating that there had likely been no air in the oil during this test. See Figures 8 and 9.

The tests indicated that the limited high frequency output was due in part to the weight of the tool—that much of the energy was going into shaking the rest of the tool rather than the wellbore, and that the output would improve if we changed some of the non-moving steel parts to aluminum, or if we could decouple a large portion of the tool weight. Our tool has a resonance determined by the weight of the tool and the stiffness of the clamp. Amoco built a new reaction mass housing, centralizer, and nose assembly out of aluminum to decrease the module weight, and Raytheon designed a feature in their clamp that would hydraulically de-couple the clamp and vibrator from the electronics module and motor/pump module. Comparison tests were made with the vibrator using aluminum parts and then using steel parts. However, it was found after the test that the effect of the aluminum vs. steel parts alone could not be easily determined, since during some of these tests the clamp nubs were loose, leading to reduced output. Figure 25 shows some of the output curves with aluminum parts and with steel parts.

A separate surge chamber had been inserted between the clamp and the actuator. This added several joints and a structural member, which resulted in a much softer spring constant than if the actuator was bolted directly to the clamp. Raytheon removed the separate surge chamber and incorporated corresponding oil chambers into un-used areas in the clamp. Comparison tests were made with the old clamp and surge chamber and with the new clamp without the surge chamber.

The source also showed lower than expected output at very low frequencies from 0 to 40 Hz. The drive signal had included a 1/3 second taper at the beginning, which accounted for some of this low output. The taper at the start and end of the sweep is used to reduce the ringing in the correlated data. The effects of changing to a 0.1 second or 0.03 second taper were modeled. The attenuation of the low and high frequencies was higher with the long taper, but the ringing and the background noise of the auto correlation were higher with the short tapers.

In the field test at La Habra, the data from the Chevron prototype was recorded using the OYO receivers, while the data for the new axial vibrator was recorded using the Exxon receivers. It is possible that some of the difference was due to the seismic receivers, rather than the seismic sources.

We discussed the relative importance of low frequency vs. high frequency output in cases where we needed to make tradeoffs. Some team members said that at very low frequencies crosswell has no advantage over surface seismic and that the high frequencies are most important for high resolution imaging. They said that in producing oil fields background noise below ~50 Hz

swamps the signals, and that they typically have to cut off the low end of the spectrum due to ~30 dB noise. Others said that they had not seen that much problem with low frequency noise, and that if the formation restricts the frequencies that the source can transmit that the source needs to have low frequency capability. Pelton said that with a linear sweep, to double the energy at the low frequencies you only have to dwell for ~.05 seconds. To double the energy at the high frequencies you would have to dwell for ~ 5 seconds. So they strongly recommend that we give up some of the output at the low frequencies and just dwell slightly longer at these frequencies.

Following extensive modeling and discussion, we decided that on the existing hardware we would move the clamp closer to the actuator, deaerate the oil, eliminate the surge chamber and the clamp adapter and three joints, that we would leave the reaction mass and stroke unchanged, and that we would re-test the source with some aluminum parts.

After the tests in La Habra, Raytheon performed a number of tests in their laboratory test facility using the Chevron clamp with the axial vibrator, including de-aerating the oil, and testing the actuator with a 50 lb steel reaction mass and no housing, for comparison to the 250 lb reaction mass. They tested at 25%, 50%, and 100% valve power, and at various system pressures. Figure 24 shows the positive effects of operating at higher system pressure. While conducting some of these tests, they noted erratic waveforms on the clamp accelerometer, and lots of harmonics on the reaction mass, and did not see the expected changes in reaction mass accelerometer output under these varying conditions. They determined that part of this was due to backlash in the clamp and clamp/casing interface. The Chevron clamp had 12 pointed nubs on the back surface. These nubs had become loose in the clamp through fretting wear. It is possible that this had occurred prior to the La Habra test, adversely affecting that data. Raytheon removed the nubs in the clamp and replaced them with interference shrunk-fit nubs and repeated the tests. The tests with the new nubs showed a marked improvement.

When the new clamp was completed, it was assembled with the axial vibrator module and tested in the lab at Raytheon during the week of December 11-15, 1995. Figure 25 shows 4 curves of the accelerometer output on the reaction mass, which shows the continual improvement in output between the time of the La Habra tests and one year later. These improvements were due to replacing the worn nubs, using lighter aluminum parts, eliminating the adapter plate and aligning the axis of the clamp with the axis of the vibrator. In addition, although the output at higher frequencies is fairly low, there is output up to 800 Hz and in later crosswell field tests, output to 800 Hz was received across large well separation distances. The Raytheon test fixture showed some force output up to 1000 Hz, but it was not clear if these were harmonics or not.

Pelton believes that the output of the tool as seen by a seismic receiver is a weighted sum of the acceleration of the reaction mass and the acceleration of the clamp. They recorded both the clamp and reaction mass acceleration and combined those two signals, taking into account the phase of the two signals. This is commonly done in surface vibrator testing. The source output vs. frequency as seen by a remote seismic receiver will be verified during field testing.

Effect of Supply Pressure
Values from Reaction Mass Accelerometer

Figure 24: Effect of Hydraulic Supply Pressure on Force Output

Measured Output of Team Vibrator
Values from Reaction Mass Accelerometer

Figure 25: Progressive Improvements to Team Tool Output

Other Vibrator Modules

It is very desirable for the source to have several axes of vibration, each with different radiation patterns, to use in different geophysics applications. The team held many discussions on the types of actuators to use for other vibrator modules and how to implement them. Some of these are listed below. Figure 26 shows the radiation patterns from some possible vibrator modules. The team decided to delay developing any of these additional modules until the whole system had been field tested. GRI later funded the preliminary design of a horizontal vibrator module with two orthogonal point forces, that could be attached to the present tool. At the time when this report was being prepared, negotiations between P/GSI and GRI for development of a single well system that will also include a horizontal actuator source were in progress. P/GSI is also planning on ordering a spare clamp and a spare electronics module. The new system is expected to be available for commercial use by the first quarter of 1999.

Horizontal Dipole Source:

B. Paulsson had tried using the clamp from the Chevron prototype tool as a seismic source by oscillating the pressure applied to the clamp shoe. At low frequency he was able to apply a 2500 psi +/- 2000 psi oscillating load. This was the basis for the originally planned horizontal dipole module for our tool. Raytheon did a preliminary design and modeling study for such a source, using a clamp with 2 fixed shoes and 1 moving shoe. There were concerns about the loads on the 3 contact points being un-equal, about producing high enough frequency output, and the source producing a non-uniform radiation pattern. One problem is that the amount of oil under compression will be at least as great or greater than in the present axial vibrator, so that compressibility of the oil will limit the frequency response of such a tool. Much of the energy would be used in simply compressing the fluid. One way to overcome this would be to use long stroke, high force pistons that bottom out on metal stops in the tool every time to allow clamping into large diameter casing yet maintain high stiffness, and a second set of short stroke, high frequency pistons with small fluid volumes for the actuator. Another proposal was for a 4 shoe pulsed monopole, similar to the Chevron Prototype clamp, but with 4 pulsed shoes at right angles to each other, rather than one moving shoe.

Horizontal Point Force Module:

Another proposal was for a horizontal two-axes reaction mass shaker. It would have a large reaction mass like the axial vibrator, but with the reaction mass vibrating side to side in the tool rather than up and down. This could be implemented using 2 reaction masses and 2 actuator systems, which has a large weight and length penalty, or a single reaction mass with 2 actuators mounted at 90 degrees to each other, which would be difficult to implement, or a single reaction mass and actuator which could be rotated 90° between sweeps. All of these would be difficult to implement in the space available, and with a reaction mass long enough to provide the required weight the tool could have resonant bending modes at fairly low frequencies. The horizontal shaker could also be implemented using either an internal reaction mass or by using the total weight of the tool floating on a clamped piston as the reaction mass. This implementation would yield an extremely low unexcited mass. This would require modeling to see if the fluid pressure waves due to the tool movement would cause significant tube waves or interfere with the force imparted to the well by the clamped piston.

Radiation Pattern for Different Actuators

Figure 26: Radiation Pattern of Different Vibrator Modules

Orbital Vibrator:

Conoco has an electric motor powered, orbital, unbalanced weight, swept frequency vibrator which produces the equivalent of two orthogonal point forces (Cole, 1997). The output is proportional to the square of the motor speed and to the offset mass. Their present tool has little force output below 100 Hz because of the small offset weight, and is limited to 400 Hz at the high end by the present motor and bearings. We discussed the possibility of not building the other two axes as hydraulic modules, just using our tool as a single axis tool and making a large electric orbital source for the other two axes using a much higher speed motor, a larger reaction mass, and the possibility of changing the mass eccentricity throughout the sweep to produce a flatter output. MTI and Conoco discussed a preliminary design for such a tool that would operate to 1000 Hz. This type of tool could complement the output from the hydraulic source, but it did not make sense to build a hydraulic version of the orbital vibrator to attach to the present tool.

Torsional Source:

Another idea was for a large reaction mass mounted to a torsional hydraulic oscillator. One of the difficulties with this is that due to the small diameter available for the reaction mass, the rotary inertia of the reaction mass is fairly small. This could be improved somewhat by making the reaction mass long and hollow like a thick walled pipe so that most of the weight is at the largest diameter possible. There were also concerns about how to make a torsionally stiff clamp. Raytheon modeled the output from such a module, and it had a significant peak at mid range frequencies. It could be possible to increase the dwell time at low and high frequencies to flatten the energy output over a broader frequency range.

Single Well Hardware**Single Well Module:**

In the original conceptual tool plan, when all three vibrator modules were going to be hung in the well simultaneously, there were passageways through each of the vibrator modules for hydraulic and electrical lines to operate the modules further down. When the decision was made to attach each actuator to the tool individually, these passages through the actuator modules were eliminated to simplify the design. This simplified the actuators, connectors, module interconnects, etc. The axial vibrator module was then fabricated without these passageways.

However, when Exxon joined the project, they were primarily interested in applying the source to single-well applications where a string of receivers is hung below the source. This requires that power, signal and control lines for the receivers pass through all of the source modules. Raytheon determined that it would be very expensive to go back and modify the existing axial vibrator module hardware to include these single-well provisions. Raytheon did a preliminary layout of a new axial vibrator module with single-well capability and planned that in the future a second axial vibrator module would be fabricated with single-well capability. They also included the copper and fiber optic lines needed to support single well applications through all of the other tool modules which had not been fabricated yet, including the motor/pump module, electronics module, and clamp.

We reviewed the requirements of various existing receiver arrays to determine what power supplies, signal conditioners, etc. needed to be included in the source to operate the receivers. The different receivers available had widely varying requirements for voltage, current, number of control and monitoring lines, need for downhole memory, digital vs. analog output, etc. We decided that rather than trying to include the necessary power, signal electronics, memory, and control electronics within the source tool to operate the receivers, that we would keep all of the support equipment for the receivers uphole at the surface, and simply run 6 copper lines and 2 fiber optic lines all the way from the surface, through the heavy duty wireline, through the source tool, and to a connector at the bottom of the source tool. This in turn would connect with a small diameter copper and fiber optic wireline leading to the seismic receivers. In that way, any receiver string that operates on a 7-conductor wireline or on a fiber optic wireline could be adapted for use with this source.

Exxon provided funding to design a single-well version of the present axial vibrator module, which would allow the use of receivers in the same well as the source. Raytheon also reevaluated the trade-offs in stroke length and reaction mass size to try to optimize high frequency output. The design has been completed and GRI funds have been secured to fabricate this hardware.

Drawings

Raytheon produced all of the detailed drawings of the source hardware. They have retained a set. Sandia has a set of drawings for the hardware built by Raytheon on Sandia's contract, and Chevron has a set of drawings for the hardware built by Raytheon on Chevron's contracts. Pelton designed the uphole and downhole control electronics under a Chevron contract, and Pelton and Chevron have complete sets of drawings for those electronics.

Overall System

The seismic source is one part of the overall seismic system. There are a number of additional parts of the system which are described below.

Control Trailer

A seismic source control trailer was setup for the tool operators. It contains the tools and benches needed for working on the source. It contains 3 Pentium computers—one for Pelton's control electronics, one for MTI's motor control, and one to display tool status. It contains winch load readout and depth controls. It also contains the control electronics and recording equipment for the seismic receivers. And there are work stations and printers for data quality checking and initial data processing. Figure 27 shows the interior equipment and the exterior of this trailer.

Generator and Transformer

The source tool operates on 480 volt 3 phase 60 Hz power, which is typically available in oil fields, either from generators or from the power grid. However, due to wireline voltage drops, 880 volts is required uphole at the motor power supply. A 480 volt 37.5 kW generator was mounted on the wireline truck to supply power, and a transformer was added to convert this 480 volts to the 880 volts required at the surface.

Simulated Wireline

Since the large Vector wireline had not yet been fabricated when Raytheon and MTI started their electric motor and electronics design work, Raytheon built a simulated wireline that duplicates the electrical properties of the large power conductors in the 20,000' wireline. This simulated wireline was shipped to MTI to help optimize the electric motor. Raytheon also tested their own electronics with a 10,000' reel of signal wire to optimize their power supply and drive signals.

Receivers

Many typical borehole seismic receivers are not designed for the high frequencies which this source will generate. We held a number of meetings on various receiver issues. Amoco had a consultant, Paul Wuenschel, document all of their past receiver tests comparing different types of borehole receivers and presenting recommendations for applicable receivers for this system. These tests included laboratory tests and field comparisons of the Exxon 5 level array, Amoco Terrel tool, OYO geophone and accelerometer tools, Texaco 5 level hydrophone, and cemented receivers. None of the tools tested performed as well as the cemented array. The hydrophones performed about as well as the clamped tools, and can operate while moving, but they do not provide any directional information. The better the receivers were clamped the lower the tube wave problems. It is difficult to compare receivers because all of them have different frequency limitations, resonances, off-axis response, etc. We decided not to settle on any one type of receiver, but to make provisions to use the source with whatever receivers were available.

Figure 27: Seismic Source Control, Shipping, Recording,

and Data Processing Trailer

A) Interior Equipment

B) Exterior

OYO Receivers:

OYO and Sandia developed a 5 level 3-axes receiver array which was specifically designed for high frequency recording (Sleeve et al. 1995). It has small, lightweight sondes with 3-axes accelerometers and digitizers which can record seismic signals with frequencies up to 2 kHz. The sondes are clamped to the wellbore using an electric motor driven shoe. They are deployed on a fiber optic wireline, which allows for continuous, high data rate recording and eliminates the need for downhole memory.

Exxon Receivers:

When Exxon joined the seismic source team they offered their 5 level seismic receiver array as part of their contribution. It was also designed for high frequency recording and has small, light weight, hydraulically clamped sondes which operate on a standard wireline (figure 15). It can use geophones or accelerometers as the seismic sensors. It was a memory tool, storing the data downhole at high speed during a sweep, and then transmitting it to the surface after the sweep at a much slower speed. This limited the amount of data that could be recorded from long sweeps or continuous recording, and took a long time to transmit between sweeps.

OYO had been working on an analog to digital to fiber optic converter module that would accept up to 48 analog inputs from any seismic receiver array, digitize them, and send them up on fiber optics in real time. Exxon and Chevron upgraded the Exxon receiver string to interface to the OYO module, and also had Vector fabricate a 20,000 foot fiber optic wireline to deploy the receivers on. They installed this wireline on a receiver wireline truck. A fiber optic line was also purchased to connect between the source trailer and the receiver trailer in cases where they are separated by a long distance.

Conoco and Amoco Receivers:

Conoco and Amoco had worked together for several years to develop a 5 level receiver string based on a design by George Terrel. Each company built their own receivers from the common design. The receivers can use geophones or hydrophones and have a traditional electric motor driven swing arm clamp. They operate on a standard wireline. They use the sondes with a Century digitizer and telemetry module. The system produces high quality data and high field reliability. With the development of the OYO analog to digital converter module they can also transmit data continuously on fiber optics.

Fiber Optic Receivers:

We met with a number of different groups who are working on developing all fiber-optic receivers which use fiber optics for both the seismic sensors and for transmitting the data to the surface, with no downhole electronics. Some of these were in the development stage, others were converted from submarine applications. Some involved clamped sensors and others were free hanging hydrophone type sensors. These fiber optic arrays have the advantage of very high data rates, potential lower cost, and the extension to very large arrays, which would decrease data acquisition time. See the Field Test section for a discussion of tests done with these receivers.

Source Wireline

Conoco had built a 10,000' heavy duty wireline containing 21 #16 copper conductors for use in powering their 4 hp orbital seismic source. They offered it to the project to power our hydraulic seismic source. However, it became apparent that the Pelton electronics could not withstand the 200 °C requirements if all of the electronics had to be downhole. We decided to leave as much of the electronics uphole as possible and send signals back and forth between the source and the tool. Because of the speed required and the long length, and also to minimize crosstalk induced noise on the control lines, we decided to use fiber optic transmission rather than copper wire. This was especially important for single-well applications, where the receiver data would have to travel through the electric motor section of the source tool and along the full length of the large AC power lines used to power the downhole electric motor. In addition, several companies were interested in deploying the source in deeper wells than the 10,000' wireline would allow.

This required that a new wireline be built that would include power conductors for the large downhole electric motor, conductors for the downhole electronics power supply, conductors for the receivers below the source, fiber optics lines to send data to and from the seismic source, and fiber optic lines for the receivers in single-well applications.

At this time we also considered using a cable inside of steel or composite coiled tubing, rather than a wireline. Coiled tubing has much higher strength than wireline, could be used to push the tool into horizontal wells, and we could supply hydraulic power to operate the actuators through the tubing from surface hydraulics. However, there were also a number of design trade-offs and some disadvantages to this plan, including temperature limitations, fatigue bending, collapse pressure limitations, need for coiled tubing injectors, etc., and we decided to use a special design wireline instead.

GRI funded the development and fabrication of the new fiber optic source wireline. We went through a number of iterations on the wireline design. There were many trade-offs in cable weight, size of conductors, conductor configuration, voltage drop, high temperature limits, high voltage limits, material selection, crosstalk, protection for the fibers, etc.

It is difficult to build extremely long wirelines because the weight of the cable itself eventually exceeds the strength of the cable. Adding additional armor or strength members simply makes the cable even heavier. This cable has a breaking strength of 64,000 lbs. It can be safely pulled to 50% of its breaking strength, or 32,000 lbs. However, the weight of the 20,000' of cable in air is 33,800 lbs, and 25,960 lbs in water. Since the working load limit is very close to the weight of the cable, it does not afford very much pull capability for the weight of the tool, dynamic loads, receivers hung below the tool, or pulling the tool free if it got stuck when the cable is fully deployed. In the event that you needed to pull hard when all of the cable was unreeled you would have to lower a cable-pulling coiled tubing down the well and grab the cable part way down to pull.

In addition to maximizing the strength of the cable and addressing temperature considerations, there were a number of electrical constraints. The 3 main power conductors for the AC motor

had to be arranged symmetrically. The signal and power lines for the downhole power supply needed to be twisted shielded pairs or quads to minimize induced noise coupling from the large power conductors. The stainless steel tube containing the fibers needed to be protected from crushing. Tension Member Technology Company reviewed the proposed cable design for mechanical stresses and suggested a number of changes.

The wireline contains five optical fibers. Two are single mode fibers for possible future use with fiber optic gyroscopes, one in the source cablehead and one for the receivers. There are three multi-mode fibers for source and receiver signals. One of these is for sending commands from the surface down to the source. Another one is for sending source tool status information up from the source to the surface. The third fiber is for sending receiver data up from below the source. We evaluated information on high temperature fibers from several companies including SpecTran, Fiber Guide Industries, Sumitomo, and Corning. These fibers had upper temperature limits ranging from 200 °C to 1095 °C. However, we had concerns about the availability of long lengths of high temperature fiber and about the ability to splice it. In addition, other insulators and sheathing materials in the cable had temperature limits that were fairly low. We had the wireline companies quote on both a high temperature and low temperature version of the cable. The high temperature cable was several times the cost of the low temperature version, so we decided to buy the low temperature version. The cable is rated at 150 °C. We received quotes from three cable manufacturers, and the contract was awarded to Vector.

The Vector cable uses Corning single-mode fiber and multi-mode fibers with high temperature acrylic coatings. The fibers are rated at 85 °C, but had been tested by Corning to 125 °C, and samples were tested by Chevron to 200 °C. The fibers were sent to Laser Armor Tech where they were encased in a protective 20,000' long stainless steel surgical tube, which is formed and welded around the fibers in a continuous operation. In the source wireline, the tube containing the fibers is helically wound with the rest of the cable members, which helps support the fibers within the tube, which is full of air. The optical fiber assembly in its protective stainless steel tube was then delivered to Vector, the cable manufacturer, for winding into the specialty wireline. Optical losses in the fiber were only 1/2 dB/km, much less than the specification. Fiber optic losses from the end of the control cable to the end of the tool, including the slip rings, were only 4 to 5 dB.

In addition to the optical fibers, there are 3 large power conductors to power the electric motor, 4 conductors to power the downhole electronics, and 6 conductors to power downhole receivers. Electrical tests were conducted to measure the capacitive and inductive coupling between the high power AC wires that power the downhole motor and the 6 conductors that pass through the tool for use in powering the receiver array below the tool in single-well applications. These 6 conductors pass all the way from the surface through the 20,000' wireline and through the electrically noisy motor/pump module and electronics module, and then on to an array of receivers. Tests were conducted for a number of communication signal levels and frequencies, while operating the source electronics and/or the source downhole motor at different power levels, as well as with the source hydraulics and/or electronics turned off. For these low voltage communication signal levels at high frequencies, there was significant distortion of the signals on these lines, which would make it virtually impossible to detect the signals. This indicated that

communication with the receiver sondes will need to use the fiber optics, as planned, and that the 6 conductors can only be used for supplying clamp power or sending high voltage low frequency or DC signals to or from the receivers.

Due to the nature of the design of this cable, the outer armor wire was loose, and remained that way even when the cable was tensioned at up to 30,000 lbs. This situation interfered with the proper spooling of the cable. It was easily corrected by removing and reapplying the outer layer of armor wires. After fabrication, the wireline was shipped to Dynacon for spooling on the draw works. During testing the cable has performed flawlessly.

Figure 28 shows a detailed description of the fiber optic source wireline. Figure 29 shows a photograph of the five optical fibers in their protective stainless steel tube, a pictorial cross-section of the cable, and a photograph of the cross-section of the cable.

Quote #3833-4f Low Temperature Instrumentation Cable

#14 AWG twisted shielded pairs
2 - #14 AWG 19/0.0147" bare copper (2.08 sqmm)
EPC insulation, OD = 0.108" (2.74mm)
2.78 Ω /kft (9.12 Ω /km) +/- 5%, rated 730 Vrms AC
2 - #20 AWG conductors in interstices
#20 AWG 7/0.0126" bare copper (0.56 sqmm)
EPC insulation, OD = 0.072" (1.83mm)
10.5 Ω /kft (34.5 Ω /km), rated 560 Vrms AC
Assembly has drain wire and foil shield
Assembly OD = 0.230" (5.84mm)
Assembly lay angle = 8.0°, lay length = 2.4"
Quantity = 2 pairs

#18 AWG 7/0.0152" bare copper (0.82 sqmm)
EPC insulation, OD = 0.080" (2.03mm)
7.02 Ω /kft (23.0 Ω /km), rated 600 Vrms AC
Quantity = 6

#12 AWG twisted shielded pair
2 - #12 AWG 19/0.0185" bare copper (3.30 sqmm)
EPC insulation, OD = 0.122" (3.10 mm)
1.74 Ω /kft (5.71 Ω /km) +/- 5%, rated 700 Vrms AC
2 - #18 AWG 7/0.0152" bare copper (0.82 sqmm)
EPC insulation, OD = 0.081" (2.06mm)
7.17 Ω /kft (23.5 Ω /km), rated 600 Vrms AC
Assembly has drain wire and foil shield
Assembly OD = 0.258" (6.55mm)
Assembly lay angle = 17.7°, lay length = 1.20"

0.078" (2.00mm) stainless steel tube
Two single mode 250 μ m acrylate buffered fibers
 ≤ 0.50 db/km at 1300, ≤ 0.35 db/km at 1550
Three 50/125 250 μ m acrylate buffered fibers
 ≤ 3.4 db/km at 850, ≤ 1.3 db/km at 1300
150 MHz-km at 850, 500 MHz-km at 1300
High temp CPC6 acrylate buffer
Tube radius of curvature = 2.7" (8.9cm)
EPC protective jacket, OD = 0.230" (5.84mm)

#7 AWG 19/0.034" bare Cu (11.1 sqmm)
EPC insulation, OD = 0.230" (5.84mm)
Rated 1350 Vrms AC,
0.513 Ω /kft (1.68 Ω /km) +/- 5%, Quantity = 3

Twisted and taped assembly
Void filled with semiconductive nitrile rubber
Assembly lay length = 4.9", angle = 17.4°
OD = 0.732" (18.6mm)

Nitrile rubber jacket, wall = 0.060" (1.5mm)
OD = 0.852" (21.6mm)
Estimated compressed OD = 0.834" (21.2mm)

A armor, low torque (not torque balanced)
Inner: 37/0.070" galvanized wires
Outer: 47/0.063" galvanized wires, coated with preservative
OD = 1.100" (27.9mm)

Nitrile rubber void filler in inner armor wire cusps

Cable weight in air = 1690 lb/kft (2515 kg/km)
Cable weight in fresh water = 1298 lb/kft (1931 kg/km)
Cable specific gravity = 4.31
Temperature rating = 150°C, ≤ 1 hour exposure; 138°C, ≤ 8 hour exposure
Cable breakstrength, ends fixed = 66,000 lb (29,930 kg)
Cable breakstrength, ends free = 61,000 lb (27,660 kg)
Recommended minimum bend diameter at storage = 22" (56cm)
Recommended minimum bend diameter at 25% of breakstrength = 44" (112cm)
Recommended minimum bend diameter at 50% of breakstrength = 60" (152 cm)

25-April-95

Vector Cable Company

Figure 28: Fiber Optic Seismic Source Wireline Description

A

B

C

Figure 29: Fiber Optic Seismic Source Wireline
 a) Fibers in Stainless Steel Tube
 b) Cross-Section Photograph
 c) Cross-Section Diagram

0.078" (2.0mm) Stainless steel tube with 2 single mode and 2 multi-mode fibers

Single Mode fibers: ≤ 0.5 db/km @ 1300nm, ≤ 0.4 db/km @ 1550 nm

Multimode fibers, 50/125: ≤ 3.5 db/km and 200 MHz-km @ 850 nm
 ≤ 1.2 db/km and 400 MHz-km @ 1300 nm

EPC jacket, OD = 0.102" (2.59mm)

Quantity = 1 tube

Cable weight in air = 339 lb/kft (504 kg/km)

Cable weight in water (sg=1) = 276 lb/kft (411 lb/kft)

Cable specific gravity = 5.4

Cable breakstrength, ends fixed = 16700 lb

Cable breakstrength, ends free = 11600 lb

Temperature Rating

300°F 1 hour service

280°F 8 hours service

250°F 24 hours service

230°F long term service

Recommended minimum bend diameter (no load) = 12"

Recommended minimum bend diameter (at 25% of breakstrength) = 22"

8-March-96
Vector Cable

Figure 30: Fiber Optic Receiver Cable

Receiver Wireline

A small diameter fiber optic wireline was fabricated for the receivers by Vector cable. A 20,000' length was fabricated for use with the receivers in a stand alone mode for crosswell applications, and a 3000' length was fabricated to make short jumpers of different lengths to connect between the seismic source and the receivers when the source is used in single-well applications. The fiber optic receiver wireline contains 6 copper conductors to power the receiver electronics and the clamp. It contains 2 single mode and 2 multi-mode fibers in a stainless steel tube. One of the single mode fibers is for a future fiber optic gyro in the receiver string, the other single mode fiber is a spare. One of the multi-mode fibers is for transmitting receiver data to the surface, the other multi-mode fiber is a spare. Since this tube with the fibers in it runs down the center of the cable, there were concerns about the fibers being able to support their own weight. Therefore, the tube was filled with gel to help support the weight of the fibers, and to cushion the fibers during winding and cable handling. Figure 30 shows the details of the fiber optic receiver wireline.

Fiber Optic Slip Rings

The cable drum on the draw works includes a set of slip rings to bring the optical and electrical signals from the rotating storage drum out to a non-moving patch panel. The slip rings were manufactured by Focal Technologies, Inc. They included 1 singlemode and 3 multi-mode fiber optic slip rings, electrical slip rings for the 3 large power cables for the electric motor, and for the smaller power conductors for the source electronics and for the receiver power and controls. The slip rings can be modified to add a second singlemode channel in the future if the fiber optic gyros are implemented. The slip rings are contained inside a water tight housing which is pressurized with dry nitrogen to exclude all moisture and contaminants.

Draw Works

A specially designed draw works was ordered from Dynacon for use with the 20,000' source cable. Dynacon builds large draw works for use on seismic survey ships and had built the specialty draw works for the heavy duty Conoco wireline. The draw works includes a diesel powered hydraulic traction winch to supply the required tension to the cable, a storage winch and drum mounted transversely on the trailer, a generator and transformer to provide the power to operate the source, a remote winch control with load and position readouts, and a Kerr magnetic cable marker and reader system for precise cable positioning to 1 part in 10,000. It also contains slip rings to bring the electrical and optical signals from the cable to the seismic source control trailer. All of the draw works components were built on separate skids to allow shipment and use on offshore platforms. The finished trailer weighed over 100,000 lbs. A heavy duty Mack tractor was purchased to pull the trailer and draw works. Figure 31 shows the tractor, trailer, uphole power supply, storage reel with the 20,000' fiber optic source wireline, the diesel hydraulic power unit for the winch, and the traction winch.

Figure 31: Wireline Truck

Tractor, Trailer, Uphole Power Supply. Storage Reel with 20,000' Source Fiber Optic Wireline, Hydraulic Power Unit, and Tractor Winch

Fiber Gyro

In many applications it would be useful to know the orientation of the tool downhole. Many mechanical gyros are large, are only rated to 125 °C, and do not work well in horizontal wells. We met with several gyroscope manufacturers, and decided to make provisions, both in the source tool and in the wirelines, for future fiber optic gyros, both in the source tool and in the receiver array. These provisions included free space in the source cablehead, a singlemode fiber for the source gyro, a singlemode fiber for the receiver gyro, and electrical leads to power the laser or LED.

Dummy Tool

A "Dummy Tool" was fabricated by Chevron to run in the well before the actual tool is used in a survey. This tool is the same diameter and length as the longest source module, it is the same weight as the overall tool, and it has simulated clamp shoes. It attaches to the cablehead on the heavy duty wireline. This tool has a number of functions. One is to make sure there are no obstructions, tight bends, or other problems that might prevent the source tool from moving through the well. It also contains a collar locator and a gamma counter for correlation with well log data.

Handling Equipment

The source tool is picked up and lowered into the well by a crane. The modules are held in place at the top of the well by a metal lock plate while the individual modules are attached to each other and then attached to the cable. Raytheon also built rolling carts to move the modules around. These can be firmly attached to the tool, spanning the flexible joints between modules. They function as strong-backs so that several modules could be lifted in one piece from a horizontal to a vertical position without over stressing the flexible joints. There are two large diameter sheaves to guide the wireline from the wireline truck into the well. The upper sheave can be held by a tripod or crane. Several shipping containers were built to carry the source and related surface equipment. Figure 32 shows the tool on the source wireline being lowered into a well. Figure 33 shows lifting all of the tool modules simultaneously using strong-backs to prevent over-stressing the flex joints.

Well Tractors

Information was obtained on well tractors used for pulling logging tools into horizontal wells. There are tools presently available that are 3.125" to 4.75" diameter and 18' to 20' long. They have multiple wheels which extend from the sides. The wheels are driven by electric or hydraulic motors and the tractor can pull several thousand pounds.

**Figure 33: Lifting All Tool Modules Simultaneously
Using Strong-Backs**

Figure 32: Tool on Wireline Being Lowered into Well

Field Tests

Prototype Tool Tests:

During the source development project the team conducted comparative tests of Chevron and Conoco's prototype borehole axial vibrators and a surface Vibroseis source at Conoco's Ponca City test site, Chevron's La Habra test site, and Amoco's Mounds test site. At the Amoco site the well separation was 300', at Chevron it was 400', and at Conoco it was 2426'.

On June 21, 1993, Conoco and Amoco performed a side-by-side comparison test of 1) Conoco's new hydraulic vibrator module in a crosswell configuration and 2) a surface Vibroseis source. The test was conducted at the Amoco Mounds test site. Both sources were located at the top of one well, and an OYO receiver was placed at the bottom of a second well, 1450' deep and 300' away from the sources. Both the borehole axial vibrator and the Vibroseis were driven using identical Pelton electronics sweep signals from 20 to 250 Hz. Good signals were received from both sources. The received signal amplitude from the Vibroseis was approximately 10 times that of the Conoco downhole tool, since the Vibroseis puts out 30,000 pounds peak force compared to the borehole tool's 6,000 lbs force. This difference in received amplitude will decrease significantly when the downhole tool is used below the weathered layer rather than at the surface. In addition, the borehole source can operate to nearly 600 Hz, while the Vibroseis is limited to less than 100 Hz.

The test at Conoco's Ponca City test site was conducted the week of October 11, 1993, using Sandia/OYO receivers. The wells were spaced 2426' apart and were located in finely layered highly fractured carbonate formations. The source depth was 700' and the receiver ran from 3180' to 700'. The receiver well was not cemented. A Vibroseis truck was located at the source well and ran sweeps for comparison. The signal from the Vibroseis were approximately 20 dB higher than the signals from the borehole sources, but were low frequency. The borehole sources were swept from 10 to 640 Hz using a 7 second sweep. Figure 34 shows comparison data between the surface Vibroseis (filtered to 7 to 150 Hz) and the Conoco borehole vibrator (filtered to 10 to 330 Hz). The figure shows the excellent p-wave and shear wave data obtained. We also tried stacking 8 sweeps, since the source was very repeatable. This was a very important test for our project because it demonstrated that downhole seismic vibrators similar to the one we were building could transmit seismic energy in difficult formations over typical oil field well spacing. The new source provides even higher signal levels over a broader bandwidth and is much more easily deployed than these prototype sources.

As part of a test of receiver systems for use with the new source, a 48-level digital hydrophone array from Allied Signal was tested at La Habra with the Chevron Prototype source. The Allied Signal hydrophone array had been developed for military applications, but is now being applied to commercial applications. It contains miniature ($\frac{1}{2}$ " x 4") sondes that include hydrophone sensors, 21 bit digitizers, and telemetry. These sondes are incorporated into a smooth cable on approximately 3' spacing, with the entire array and cable having a diameter of 1.1". The present system operates to 70 °C and 2500' depth, but Allied Signal indicated that in the future they could increase this to 200 °C and 20,000' depth, and the number of sondes to 200 sondes immediately

Seismic Source Test at Conoco Test Site, OK Surface Vibrator Versus Downhole Seismic Vibrator

Figure 34: Comparison Test of Surface Vibroseis and Conoco Borehole Vibrator

and up to 1000 in the future. During the test, the receiver array was moved 8 times, giving 384 receiver stations in a total of 90 minutes. Figure 35 shows the Allied Signal digital hydrophone hardware. Figure 36 shows the data collected by the Allied Signal receiver array and the Chevron Prototype axial vibrator (Haas, 1996).

System Integration and Checkout Tests

A number of laboratory tests were conducted of individual components, sub-assemblies, and complete modules. All of the equipment in the seismic source system was finally completed in January, 1997. The entire system, including the tractor, trailer, heavy duty drawworks, 20,000' source wireline, cablehead, motor/pump module, electronics module, clamp, and axial vibrator module were assembled and tested at Raytheon. Raytheon had drilled two shallow cased wells at their facility for testing the tool, but due to poor weather, tested the tool inside. The modules were arranged in the lab with the axial vibrator and clamp in a test fixture, and hoses and jumper cables connecting the modules. The tool was controlled from the Pelton uphole electronics and powered through the wireline. Sweeps were sent down the wireline to the tool. All of the tool functions were operated. The signals from the tool diagnostic transducers were verified. The fiber optic telemetry system was tested, including measuring total system optical losses. The overall optical loss in the fiber optic telemetry system, including slip rings, wireline, and connectors, was only 4 to 5 dB, much better than expected. Everything functioned correctly. The large amount of power sent through the cable to operate the motor did not adversely affect the tool electronics. When the motor/pump module was tested over the 20,000' wireline, the electric motor efficiency was 92% and the pump efficiency was 88%. The motor had a temperature rise of only 30 °C when operating in air at full load, which was very encouraging for operation in hot wells. A few minor tool modifications were made to minimize galling, to reduce internal heating from the downhole electronics, and to provide better regulated downhole electric power.

Following these laboratory tests the system was shipped to La Habra, California, for tool checkout, total system integration and geophysical tests. Following these it was used in several commercial surveys.

Beginning on February 22, 1997, we conducted initial system checkout tests in a well at Chevron's test site, to verify the tool's operation, and to accept delivery of the Sandia portion of the hardware from Raytheon. We inspected the source tool and all of the system support equipment. This included the instrument control trailer with its manual winch controls, computer winch controls, tool diagnostic display on laptop computer, Pelton sweep controls, Raytheon tool power controls, downhole motor control laptop, tool depth control system and recorder, receiver control and computer, and data processing workstation, the source handling equipment including sheaves, crane, tool cradles/handling carts, the source wireline truck with the 20,000' fiber optic

Borehole Acquisition & Telemetry Cans

Telemetry Can Electronics

Acquisition Can Electronics

Borehole Seismic Sensor Array

Figure 35: Allied Signal 48 Sonde Receiver Array

Cross Well Seismic Data - AlliedSignal Hydrophones & Chevron Downhole Vibrator

Receiver: AlliedSignal 48 Level Digital, Thin-line Hydrophone Receiver Array

Downhole Seismic Source: Prototype Clamped Vibrator, Sweep: 7 Sec. 10-640 Hz

Recording System: Alliant Techsystems, AESOP Seismic Recording System

Depths Source: 500 ft, Receivers: 170 to 1573 ft, Distance: 400 ft, Correlated Data, Site: Chevron, La Habra, CA

**Figure 36: Data from Allied Signal Receiver Array
and Chevron Prototype Source**

cable, optical slip rings, tension drive and level wind, uphole electric generators for the source and for support equipment, the dummy tool, the Exxon receivers, and the receiver wireline truck.

The source tool was hooked up to the wireline and was lowered approximately 75' into the well. All of the uphole power and control electronics were connected and functionally tested. The electronics module was tested, the downhole hydraulic module was turned on and tested, the clamp was operated a number of times, and the tool temperatures, pressures, LVDT readings, and other parameters were checked. Several sweeps were run. Following these tests in the dry well, the well was filled with water to the surface. The tool was again clamped and several sweeps were run from 5 Hz to 800 Hz. The sweeps were recorded by an Exxon receiver string located in a second test well. The received signal showed a high signal to noise ratio. After operating the downhole motor continuously for 1 ½ hours (drawing 12 to 13 kW), the motor oil temperature was steady at 67 °C and the electronics module and the water surrounding the tool both reached 45 °C. Based on the results of these tests, we accepted delivery of all of the Sandia owned hardware from Raytheon.

Geophysical Tests

Geophysical tests of the overall system were conducted beginning March 5, 1997 at Chevron's La Habra test site (Paulsson and Fairborn, 1998). The first test was a common source fan with the CRADA source at a depth of 500 feet and the Exxon receivers moved from 1500' to 150' deep. The second test was a common receiver fan with the receiver at a depth of 500 feet and the source moved from 1500' to the surface in 10' steps. The distance between the source and receiver wells was 400 feet. A single 4-second sweep from 10 Hz to 800 Hz was used at each level. This was a direct comparison to earlier tests of the Chevron prototype source at this site and at these depths. The data quality from the new tool was excellent. Compared to the Chevron prototype, the new source had greater bandwidth (5 to 800 Hz vs. 5 to 640 Hz), less distortion, and higher repeatability. As can be seen (figure 38), the new tool has much higher signal levels, strong clear p-wave first arrivals, and much higher shear wave energy. Some reflections appear in the data from the new tool that are completely absent from the prototype tool data. There is very little tube wave energy apparent in the received signals. There is significant received energy out to 800 Hz, the upper end of the sweep frequency. There is some indication of a reflection at 950 msec, which implies a travel path of over 8,000'. The hardware functioned well. Operational procedures were developed, and a number of minor hardware and software modifications were made.

Figure 37 shows an overview of the La Habra test site with the source system on the left and the receiver system at the right. Figure 38 shows a direct comparison of the data from the new vibrator and the Exxon receivers on the left, with the Chevron Prototype and the OYO/Sandia receivers on the right. Figure 39 shows the received traces and received power spectrum from the new tool. Note that there is received energy out to the full 800 Hz of the sweep. Figure 40 shows a longer recording time period from the La Habra test, with apparent returns at 950 milliseconds.

Figure 37: La Habra Test Site Overview

Source

Dept: 500 ft
One 4 sec Swcep
10-800 Hz
Filter 25-50-700 Hz

Receiver

Exxon 5-Level Array
150-1500 ft
10 ft Spacing

Site

La Habra Test Site
Well Spacing 400ft

Test Data

March 3, 1997

Display

Trace Equalized

A **B**

Figure 38: Comparison Tests at La Habra Field Site
a) Team Vibrator with Exxon Receivers
b) Chevron Prototype with OYO/Sandia Receivers

Source
 Depth: 500 ft
 One 4 sec Sweep
 10-800 Hz
 Filter 25-50-700-900 Hz

Receiver
 Exxon 5-Level Array
 150-1500 ft
 10 ft Spacing

Site
 La Habra Test Site
 Well Spacing 400 ft

Test Date
 March 3, 1997

Display
 Trace Equalized

A

B

Figure 39: La Habra Test of Team Tool
A) Received Traces
B) Received Power Spectrum

Source
 Depth: 500 ft
 One 4 sec Sweep
 10-800 Hz
 Filter 25-50-700-900 Hz

Receiver
 Error 5-Level Array
 150-1500 ft
 10 ft Spacing

Site
 La Habra Test Site
 Well Spacing 400 ft

Test Date
 March 3, 1997

Display
 Trace Equalized

**Figure 40: La Habra Test of Team Tool
 1 second window**

During March 1997, additional tests of the source were conducted using a 6-level, all fiber optic hydrophone array from Litton (Paulsson et al, 1997). The Litton system uses a single-mode fiber for each sonde. Laser light is transmitted from the surface, through the fiber, to the sonde, where it is split into two paths, one path designed to change in length due to pressure changes, and the other reference path designed to be unaffected by pressure changes. The optical signal is sent back to the surface, where an interferometer and phase detector sense the changes in the sonde due to pressure waves. Litton had tested their array earlier with air gun arrays in seafloor seismic applications, and in towed streamer systems. They report that their system has a dynamic range of ~ 140 dB. The system senses changing signals, and can reject DC offsets due to temperature and pressure. A much larger receiver array, based on the Litton, Allied Signal, or other large receiver arrays could dramatically reduce the time required to acquire a crosswell data set.

First Commercial Test

The first commercial oil field survey using the source tool was conducted by P/GSI for Union Pacific Resources Company (UPRC) at Carthage, in east Texas, in early May, 1997 (Paulsson and Fairborn, 1998). The source was placed in one well, and receiver data were collected using cemented 3-component geophone arrays installed in two different wells. The purpose was to determine formation velocities for fracture mapping monitoring in future hydro fracture experiments. Both a crosswell and a reverse VSP were conducted. The crosswell spacing was ~1300'. The source was operated at depths of 5000' to 6000', and the receivers were located at depths of 7330' to 9690'. Data were plotted for single 10-second sweeps from 10 to 360 Hz at each source location. P-waves and S-waves with excellent signal to noise ratio were obtained for source-receiver separation distances of 2800', and the P-waves were still very strong at a source-receiver separation distance of 3900'. The formation velocity was 16,000 ft/sec, and the processed data showed a reflector at 1 second, indicating a round-trip distance of 16,000'. A total of 20 source sweeps were recorded, but due to problems with the recording system, the data was overwritten by each succeeding sweep, so only one sweep was finally saved. Data from an array of 112 surface geophones were also recorded, but a nearby diesel gas compressor caused a high level of ambient noise in the surface data. Some equipment problems with an uphole motor controller ended the survey early. That hardware is being repaired and modified. Figure 41 shows a direct comparison of the data taken at Carthage Texas. The data on the left is from the new team vibrator. The data on the right is from 120 gram prima cord perforating gun.

Second Commercial Test

The second commercial oil field survey using the source tool was conducted by P/GSI at Bayou Choctaw in Louisiana, which is part of the Strategic Petroleum Reserve, in conjunction with an ACTI project to image salt dome flanks. The Salt Imaging Consortium (SIC) was formed to develop algorithms and procedures for conducting reflection surveys from salt dome flanks. As part of their project, they planned a number of field tests of various sources and receivers. The

Figure 41: Carthage Texas Test

a) Team Vibrator

b) 120 gram Prima Cord Perforating Gun

sources they tested included an airgun, hydraulic vibrator, piezoelectric vibrator, and an orbital source.

This was a two well test, with the source in one well near the salt flank, and a receiver string in a nearby well, looking for reflections from the salt flank. The test, using the new axial hydraulic vibrator, was conducted in June, 1997 (Paulsson and Fairborn, 1998). Six full days of field work and more than 300 source sweeps were completed. One complete "source scan" (i.e., fixed receiver depth and multiple source depths) of seismic data was recorded with the axial vibrator. Exxon's three-component borehole geophone array was used for the seismic receivers. This was the first test of the Exxon 5 level receiver string using the OYO universal analog-to-digital interface and fiber optic telemetry, which worked well.

Strong, clean signals were received from direct arrivals in a common receiver fan and the high power output of the source was readily apparent. There were some indications of reflections from the salt flank, as well as reflections from structures within the salt dome such as the oil caverns. The data are broadband, and exhibit good signal-to-noise ratio. Well-to-well propagating P and S waves are clearly visible. Strong tube waves, possibly generated at source positions where the well cement bond is poor, are also evident. To date the Salt Imaging Consortium has not made any public release of the data from these field tests, therefore it is not presented here.

An equipment problem with the downhole electronics power supply forced a postponement in operations. P/GSI will return to Bayou Choctaw to complete the remaining data acquisition required for the Salt Imaging Consortium (SIC) contract. The equipment problem involved overheating of the electric chokes for the motor controller, and overheating of the downhole electric motor. This turned out to be due to a restriction in the coolant circulation, and has since been remedied. When the test is completed, the Exxon receiver string will have been increased to 10 levels. Successful recording of this data set marked the completion of the field data acquisition phase of the seismic source CRADA project.

Third Commercial Test

The third commercial survey using the source tool was conducted by P/GSI for Union Pacific Resources Company. Data from this test will be published in an upcoming paper (Paulsson and Fairborn, 1998). This was a Reverse Vertical Seismic Profile (RVSP) in UPRC's Busby A-5 gas well near Henderson, Texas. The survey was co-funded by the Gas Research Institute (GRI). The survey was conducted from August 15 through August 23, 1997. The survey was a test of the RVSP application for the recently developed borehole hydraulic vibrator, which is the first non-explosive source believed to be powerful enough for this type of survey. In conventional VSP's the source is located at the surface and the receivers are placed in the borehole. In a RVSP the source is placed in the borehole and the receivers are placed on the surface. This allows the use of hundreds or thousands of geophones. For the Busby survey, 192 geophone stations were laid out in a 16,000 foot, north-south line centered on the well.

Because of mechanical problems with the vibrator, data from only 5 source depths were recorded. Signals in the form of direct P-waves could be seen from three depths: 2000, 4000, and 5000 ft.

Since the vibrator had mechanical problems towards the end of the survey, the poor data from the 6,000 ft and 6,500 ft source depths was likely due to the reduced force output of the source.

P/GSI migrated the reflections using a VSP-CDP transform and the nearest sonic-log velocities from the Carthage 21-10 gas well, which is 20 miles away. With the source located at a depth of 2000 feet, several reflection events are observed in the data between the depths of 2000 and 4000 feet, in spite of the reduced vibrator performance and the surface noise. With the source located at a depth of 5,000 feet, the data shows coherent reflection events from offsets ranging from 2,000 ft to 8,000 ft. These events originate from a depth of 7,000 feet, which is 2,000 feet below the source. There is also an event in the data with the source at 5,000 feet that can be interpreted as a reflection from around 8,000 feet on the south side of the line.

In order to reduce ambient noise during recording, every other geophone group was buried approximately 2 feet below the surface. The difference in noise level and signal quality between a buried group and its adjacent unburied counterpart was marginal. The waveforms from the buried groups are a little sharper, but there was no apparent improvement in signal to noise ratio.

The ambient noise levels were very high, with 60 Hz and its higher harmonics being particularly troublesome. On many traces the 60 Hz noise is 500 times higher than the average noise level, which in turn is over 100 times higher than the average noise level normally seen in borehole data using the same OYO DAS-II recording system. There may simply not be enough dynamic range in the system to record low-level reflections on the noisiest channels. Much of the recording was done after a rainstorm, making the geophone spread particularly susceptible to electrical interference. Even though the connectors were designed to be waterproof, some leakage must have occurred allowing ground currents to be picked up by the cables.

Conclusions

A complete advanced borehole seismic source system with all associated field equipment is now commercially available to the oil industry through commercial companies. Despite significant technical challenges, very ambitious program goals, and diverse customer requirements, the Team has successfully developed a new tool with significantly greater capability than existing borehole vibratory sources. All of the team companies contributed significantly to the success of this project. The present tool operates an axial vibrator module, but provisions were made for attaching other vibrator axis modules, and also to accommodate single-well imaging. The system is designed for use in wells with 5.5" and larger casing, to depths of 20,000', and has an upper temperature limit of 150 °C, which could be increased in the future. The source produced useful output from 10 to 800 Hz. It has force and phase control, and extensive tool diagnostics. It incorporates a fail-safe clamp. A new service company, P/GSI, was formed to perform surveys with this hardware. Three field surveys have been conducted, at Carthage, Texas, Bayou Choctaw, Louisiana, and Henderson, Texas, and additional surveys are planned to show the utility of the data. There were some operational problems with the tool. Hardware issues identified in these surveys have been addressed to improve field reliability. The data from the field tests has been excellent. The data quality, the operational capability, and the ease of deployment of this tool are all greatly improved over the original Chevron prototype. If the surveys can be performed economically, it is anticipated that there will be a large increase in the number of high resolution crosswell surveys performed and a resulting increase in the recovery of oil.

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