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Technology Introduction

The Oil Program began to focus on seismic technology in the late 1980s. The Oil Program had conducted a major demonstration program beginning in the mid-1970's to develop and demonstrate enhanced oil recovery to recover more of the oil left after conventional and waterflood recovery. Twenty-seven projects in this demonstration program were high-risk but that had an excellent benefit potential if the process was successful. Post mortems of many of the unsuccessful projects highlighted the primary reason for failure was a lack of reservoir characterization. The DOE/FE then began the process to identify those reservoir characterization technologies that were needed to reduce risk and enhance success of enhanced oil recovery technologies.

There are many technologies that DOE has supported for characterizing reservoirs, including: seismic, electromagnetics, acoustics, chemical tracers, coring the rocks with the associated drilling and analysis processes, geology of outcrops for analog use, and well logs using electrical, acoustic, and nuclear technologies to measure rock and fluid parameters

Reservoir characterization activities have been conducted essentially since the 1950's during the then Department of Interior's Oil Program, which later became the Department of Energy's Oil Program. As the programs evolved since 1978, seismic development, became a major focus when, in 1988, the Oil Recovery Technology Partnership was formed. Through the Partnership, the National Laboratories bring their technologies developed for defense purposes to bear on seismically measuring crude oil reservoirs. The producing industry determines which technologies will be addressed and, even further, which part of each technology will receive attention. Seismic technologies, due to their importance for increasing production and reducing costs of operations, have received the majority of the Partnership's attention. Each project chosen for implementation requires an industry partner(s), cost sharing, and a National Laboratory to act as lead for the project. This ensures the work is needed, relevant, and will be used once developed.

The Department also started a demonstration program in 1992, the Reservoir Class Program, to focus on reservoir characterization as a necessary tool for designing demonstration projects. A majority of the 32 projects initiated from 1992 through 1995 have developed new or adapted seismic technologies for application in fluvial-dominated deltaic (Class 1), shallow shelf carbonate (Class 2) and slope and basin clastic (Class 3) reservoirs.

The Importance of Seismic Technology

Seismic technologies are geophysical techniques used to image oil reservoirs, the associated rock and fluids from the earth's surface and/or from nearby wellbore. The application of seismic in oil exploration and development has increased ultimate recovery, reduced risk and costs by identifying barriers and pathways of fluids movement through the reservoir, thus allowing for more effective targeting of well placement and management of enhanced oil recovery projects.

Since 1978, improved seismic technologies, using vastly improved computer processing capabilities, are responsible for much of the large long-term reductions in finding costs and increases in exploration and development well success rates both onshore and offshore. In addition, modern seismic technologies have contributed greatly to huge increases in Gulf of Mexico (GOM) deepwater and subsalt production and proved reserves, especially since 1992.

Reductions in Finding Costs: Through the application of improved seismic technologies and increased efficiencies of operation, major oil companies have been able to reduce finding costs from $25/BOE to about $5/BOE (BOE = barrels of oil equivalent, including both oil and gas) for U.S. offshore operations and from $20/BOE to $5/BOE for U.S. onshore and foreign operations between 1981 and 1994. Finding costs again increased somewhat between 1994 and 1999 due to higher costs associated with GOM deepwater and subsalt activities, and because low oil prices caused downward revisions in "booked" reserve values. From late 1999 to date, overall finding costs for many major oil companies have tended to return to the $5/BOE baseline.

Increased Exploration and Development Well Success Rates: Seismic applications have evolved rapidly over the past twenty-five years, from mainly exploration (using 2-Dimensional and some 3-D) to exploration and development (using 3-D, 3-D/3-Component and 4-D [including time]) resulting in increased successful well completions rates. Exploration well success rates (for both oil and gas) have increased from an average 23% from 1973 to 1975 to an average of about 33% from 1994 to 1999. This represents a 45% improvement in only 25 years! Development well success rates have improved from an average of 78% to an average of about 85% over the same time period.

Increases in exploration and development well completion rates means that while fewer wells have been drilled between 1981 and 1998, considerably more oil and gas is produced per well thus increasing recovery efficiencies. Oil production per successful oil well drilled per year during this time frame has increased by 330%. While the number of successful wells have declined by about 84%, the overall decline in U.S. oil production during this period has only fallen by about 30%. The implication is that through the increased emphasis on seismic and other technologies over the past 20 years, industry has been able to become much more efficient in finding and developing oil and gas resources and thus slowing the rate of overall U.S. oil and gas production decline.

Increased Gulf of Mexico Deepwater Production / Proved Reserves: The application of three-dimensional (3-D) seismic imaging (today's leading imaging technology) in Gulf of Mexico exploration and development efforts has led the way to the revitalization of this important oil and gas prone region. The use of 3-D seismic has resulted in exploration well completion success rates doubling to 40 % between 1985 and 1994. Oil production from this region has increased by 39% between 1992 and 1998, to where the Gulf of

Mexico presently provides about 16% of the total U.S. oil production and about 25% of the total gas production.

In 1998, 46% of the total GOM oil production and about 15% of the total GOM gas production was derived from the deep water portion of this region. Oil reserve growth in deep-water U.S. Gulf of Mexico region has increased by almost one Billion barrels between 1992 and 1998. Deep water area gas reserve growth during the same time frame was 4.3 Trillion cubic feet or a 130% net increase. The deep water natural gas liquids proven reserves increased to 42% during this same time period. Most of above proven reserve growth in this portion of the Gulf of Mexico can be directly attributed to improvements in seismic technologies and associated advancements in drilling, completion and production technologies directed toward these deep water reservoirs.

Subsalt Production and Proven Reserves in the Gulf of Mexico: It is estimated that 1-10 billion barrels of oil lie beneath the salt features in the Gulf of Mexico. There have been 13 successful exploration and development tests through mid-1998 that should add reserves to those of the Mahogany, Enchilada, and Gemini giant reservoirs (greater than 100 million barrels reserves) found through this process. This opens up potentially great reserves in reservoirs underlying salt deposits throughout the world.

Although modern geophysical/seismic technologies have contributed greatly current industry efficiencies, additional technical challenges remain in maximizing the usefulness of seismic techniques. The development and fielding of 3-Component and 4-Component systems (Primary-waves and Shear-waves in a 3-D data package) requires more R&D to more fully quantify the P-wave and S-wave responses to specific reservoir properties. Vertical resolution of seismic is still restricted to the scale of facies or 10-30 feet vertical. Smaller features, such as thin reservoirs and fractures, cannot be resolved at this time. Depending upon the geologic, often it cannot be determined with any degree of certainty what the fluids/gas are within the reservoir based on the seismic data.

The DOE Role

In alliance with the oil and gas industry and academia, the Department of Energy (DOE) has conducted and continues to conduct RD&D to develop and improve advanced seismic technologies including: cross-borehole (or cross-well), geophones and geophone arrays; vertical profiling; large downhole seismic sensor arrays; 3-D seismic; 4-D or time lapsed seismic; multi-component, multi-station borehole receivers and other advanced sensors; single well and subsalt seismic; binary explosive sources; and microborehole instrumentation. Along with new seismic tools and methods, DOE has concurrently created and implemented many of the newer, more advanced computerized seismic processing technologies, models and simulators including: the SEG/EAEG model data set, improved pre-stack Kirchoff migration for complex terrains and structures, inversion of full waveforms seismic data for 3-D, use of Bayesian Stochastic Inversion for improved petrophysical interpretation, etc. Seismic technologies have been used for investigations in shales and fractured reservoirs, injection monitoring of waterfloods and CO_2 floods, and optimization of infill drilling.

DOE's emphasis on seismic technologies RD&D has greatly increased over the past 10 years, in parallel with growing industry interest in applying these new technologies. The relationship of seismic technology to the current Oil Program is described in *Oil and Gas RD&D Programs* (1999, DOE/FE-0386)

SECTION A

FE 1. For each of the technologies identified, describe the products resulting from DOE's R&D investment that:

a) **have developed technologies that are commercially viable either today or in the near-term (2-5 years) future. What was the DOE's role in the development of these technologies?**

- ### Crosswell Seismic Instrumentation, Three-component Seismic Source

  Industry/National Lab Partnership, Sandia National Laboratories

  The first component of the original "Crosswell Seismic Imaging Project," *the three component seismic source,* was completed by Sandia National Laboratories working with Amoco, Chevron, Conoco, E-Systems, Exxon, Gas Research Institute (GRI), and Pelton in FY 1998.

  The crosswell seismic imaging technology minimizes subsurface interference and provides significantly enhanced resolutions of geological impressions. The technique is capable of "seeing" geological objects 5 feet across in comparison to 50 feet across using the traditional technology.

  Widespread use of borehole seismic techniques is possible through the development of this powerful, non-destructive vibratory seismic source. This clamped vibratory source makes a high-force, wide-bandwidth, three-axis seismic source commercially available for crosswell, reverse VSP, and single-well seismic surveys. The source makes these surveys viable over the distances typically separating wells. The three-component source consists of a downhole electronics module, a downhole hydraulic power supply module, and one of three interchangeable vibrator modules.

  The vertical vibrator module contains a high-bandwidth hydraulic actuator and a reaction mass. A complete single-axis version of the tool includes all downhole and uphole support equipment, the electronics module and hydraulic power supply module, and surface control electronics.

  The tool is designed for use over wide well spacings (~2000'), in deep wells (>15,000'), and at high temperatures (>150° C), the tool's characteristics also include: the capability to attach a seismic receiver string below the tool, fiber optic telemetry from tool to surface, 6000 lb peak force, and a present useful bandwidth ~30-500 Hz (with extension to ~800 Hz planned). The three-component vibratory source is intended for easy deployment on special heavy-duty wireline and is clamped for good coupling to formation.

- **Crosswell Seismic Instrumentation, Multistation Borehole Seismic Receiver**
  Industry/National Lab Partnership, Sandia National Laboratories

  This project developed and in ------ made commercially available an advanced three-component multistation borehole seismic receiver. The receiver's modular capability allows establishment of receiver strings that operate without time penalty, through use of the advanced receiver sonde developed by project participants.

  Digitizing circuitry transfers digital data between sondes in a receiver string. Output is sent to a data formatter/telemetry module that converts data to optical signals. Rochester developed a fiber optic wireline, operational to 200°C and containing 7 conductors and 1 multimode fiber, to carry signals to the surface. Interconnecting up to 30 sondes, a string can collect 1/8 msec sample data in real time.
  Shorter and lighter (1.6" L x 4" O.D., 30 lbs) than most receivers, the newly developed sonde has ~2000 Hz mechanical resonance, an improvement over 150-400 Hz receiver resonances previously available. Sondes use an advanced three-axis accelerometer to improve noise characteristics at high frequency, and incorporate a new wall locking piston type clamp to improve bandwidth.

  The advanced three-component multistation borehole seismic receivers are designed for 10,000 psi external pressure and >125°C well temperature. Field tested in a number of surveys, the receivers are commercially available from OYO-Geospace, or as a field service through Bolt Technology Corp.

- **Subsalt Seismic Imaging**
  Industry/National Lab Partnership, Los Alamos National Laboratory

  The most widely used technique for exploring offshore areas is seismic imaging. However, conventional seismic imaging techniques fail to locate oil-bearing sediments below or adjacent to the salt structures that cover more than 40 percent of the Gulf Continental Shelf. New seismic imaging techniques are needed to efficiently develop the estimated 15 billion barrels of oil (or gas equivalent) lying under large irregularly shaped salt features offshore in the Gulf of Mexico.

  A team of Amoco Production Company, Marathon Oil, Phillips Petroleum, Louisiana Land and Exploration, and Western Atlas International, in partnership with DOE's Los Alamos National Laboratory, working together developed advanced seismic processing techniques to increase image resolution at greater depths. In -------, the research team developed three new algorithms to help resolve some of the complex characteristics inherent in 3-D subsalt imaging.

The technology has spurred 16 producers to drill a total of 25 subsalt wildcats in the Gulf. Seven successful discoveries have been reported so far. Industry experts predict at least a 30 percent success rate for subsalt drilling in the Gulf using enhanced seismic processing and modeling techniques. Three of the announced discoveries contain reserves of more than 100 million barrels of oil equivalent each.

- ## 3-D Seismic Data Processing and Modeling, Fourier Method
  Industry/National Lab Partnership, Los Alamos National Laboratory

With increased emphasis on finding petroleum in regions of complex structure, there has been a need to develop migration approaches that provide more reliable images of complex regions than can be obtained using the standard Kirchhoff approach while at the same time maintaining a computational speed comparable to that of Kirchhoff methods. As part of that effort, researchers at Los Alamos, working with ----- have developed a suite of migration methods that are implemented in the wavenumber and space domains and operate on data in the frequency domain.

The two methods that have developed, whose implementation procedure is similar to that of the well-known split-step Fourier method, are the extended local Born Fourier migration approach and the extended local Rytov Fourier migration approach. Both of these new methods use approximations that are less restrictive than the conventional split-step Fourier approach. Tests using several numerical data sets demonstrate that they give better images than those obtained using the split-step Fourier approach.

Comparisons have been made of migration images obtained from a subsalt prestack dataset using, a standard (first-arrival) Kirchhoff migration, the Fourier migration methods outlined above, and a complete finite-difference calculation. The image obtained with the extended local Rytov Fourier method is superior to those obtained by the other methods. It provides more information about strata beneath the salt and the events beneath the salt are more consistent with those away from the salt. Some of the horizons continue up almost to the salt in the image we obtained. The computational efficiency of the extended local Rytov method approaches that of the Kirchhoff method, migrating the two dimensional data set only about five to seven times slower than the standard Kirchhoff method; the computational efficiency of the Rytov method is far superior to the finite-difference method, migrating the dataset about fifteen times faster.

- ## 4-D Seismic, Lamont Doherty Earth Observatory

This 4D seismic technology developed in 1994, superimposes seismic surveys acquired by different companies using different acquisition parameters.

Comparison of seismic response at different times allows identification of bypassed reserves.

The 4D developed by this project has been patented and is currently being marketed by Baker Hughes (Western Geophysical Division), a major petroleum service company, that has a third-party license. Western Atlas paid $2,500,0000 for the exclusive license, ongoing royalties to the university plus $4,000,000 commitment for research to look at improving the technology. Recently Western atlas announced 23 new boats designed specifically for the acquisition of 4D/4C data, with the fist three already launched and Active in the North Sea (Western Eurotour, April 1997.) By 2010, 50% of all seismic acquisition will be 4-D (Walter Lynn, PGS Tensor CEO, Offshore Technology Conference talk, May 1997)

- **4D Seismic in Texaco's Vacuum Field CO2 Project, New Mexico**

An expected 10% increase in oil recovery of the OOIP in Texaco's Vacuum CO2 Project in New Mexico is due to the 4D effort. Texaco hopes to save $8-10 million in well costs; $100 million to be invested in reservoirs over the next 5 years (4D Consortium Meeting, January 1997, Texaco press release August 1997)

- **3D Seismic Interpretation for Reservoir Characterization**
Strata Production Company, Brush Canyon Pool, Nash Draw Field, Eddy County, New Mexico

Vertical 3-D seismic profiling and modeling technology developed by Robert Hardage, University of Texas, Austin as part of this project has been used to identify structural anomalies and identify horizontal drilling prospects. The Brushy Canyon site has restricted surface access because of a playa lake and surface potash mining on the oil lease area. No previous seismic data existed for Nash Draw Field.

A standard seismic modeling package was initially used for modeling Nash Draw. Hardage developed several modifications to this software using instantaneous frequency as a coherency/continuity parameter. The time-to-depth conversion modification allowed for visualization of the Nash Draw zones under the playa and potash mining areas.

The seismic analysis showed that significant reservoir compartmentalization exists at Nash Draw field, was able to delineate the compartments. The new methods allowed for identification of productive pay zones and imaging of thin-bed turbidite reservoirs in the Brushy Canyon Unit. Based on identification of reservoir compartments the project has been modified to drill

6 additional wells under the playa lake and potash mining area to access the 584,000 bbl of additional oil reserves discovered.

In two detailed papers published in 1998 in *Geophysics* (vol 63, no 5) Hardage describes the new technique. Following publication, Dr. Hardage was contacted by the original software company, and asked to incorporate the new methodology into future seismic software package. This is expected to be available in the next 2-5 years.

- ## New Seismic Inversion Model for Reservoir Characterization
  Laguna Petroleum, Foster and South Cowden Fields, Texas

  Laguna developed a new Seismic Inversion Model based on reprocessing 3-D seismic data to improve vertical resolution of seismic inversion model traces. Reflection time errors, in the form of inaccurate time structure, present in the original data were eliminated.

  Seismic inversion modeling is a computer-applied process by which normal seismic traces (wiggle amplitude) are converted to log-like traces. The process converts the conventional seismic response to a quantitative set of data directly related to engineering concerns.

  Results of the seismic modeling at Foster and South Cowden fields aided in the identification of the San Andres formation as a "thief zone" to production from the Upper Grayburg in this area. Determination not to penetrate the San Andres and produce only from the Upper Grayburg, increased oil production, and decreased water production. The operator realized savings to the project of $30,000 per well.

  The 3-D seismic survey identified an additional 570,000 barrels of new reserves in Foster and South Cowden fields. Using the Seismic Inversion Model cost-effective interpretation technique these reserves were added at a cost of only $0.20 per barrel.

  The PI for the Laguna project has been hired to employ the technologies developed in the DOE project including seismic interpretation and recompletion technologies to address similar problems at a field within several miles of the DOE demonstration site. Work at the neighboring field will begin in late August or September 2000.

- ## Seismic Applications in the Williston Basin
  Luff Exploration Company, Williston Basin, South Dakota, North Dakota, and Montana

  Luff used 2-D and 3-D seismic as an exploration tool in the southern Williston Basin to identify drilling locations in the Red River and Ratcliffe formations.

2-D seismic has been used to locate both Red River and Ratcliffe reservoirs in the Williston Basin, but significant oil has been bypassed. Improved reservoir characterization of the Red River and Ratcliffe for the project was based on reinterpretation of old 2-D seismic surveys and new 3-D seismic surveys.

Two 3-D surveys in Bowman County, North Dakota targeted the Red River formation and revealed the complexity of reservoir porosity. Analysis identified areas of by-passed oil in the Red River. Three new wells were drilled based on these 3-D seismic surveys. Seismic data was particularly useful in identifying small reservoir compartments on the flanks of small Red River structural features. The area of amplitude anomalies identified ranged from 40 to 160 acres each.

A 3-D seismic survey and a special shear-wave seismic survey were obtained in the Ratcliffe area of Richland Co., Montana. The shear-wave survey was a failure, but 3-D seismic data indicated Ratcliffe reserves.

The project did not develop any new seismic technologies, but did for the first time demonstrate the success of 3-D seismic in identifying small compartments on the flanks of Red River structures at depths of 8,500 to 9,500 ft. in the Williston Basin. This information was made public at several workshops in the Williston Basin, and through DOE publications. Several potential drilling areas were identified from the 3-D seismic surveys, and Luff Exploration has continued to follow up on these discoveries with new drilling after the DOE project was completed.

- **Thin-bed Seismic Attribute Analysis**
  Diversified Operating Corporation, Sooner Unit, Denver Basin, CO

Diversified used 3-D seismic data analysis techniques to identify reservoir architecture and tailor well spacing and injection patterns to reservoir compartments. A seismic attribute correlation technique that successfully quantified prediction of gross and net pay thickness was developed.

The D sandstone is a seismic thin bed at the frequencies recorded at the Sooner D sandstone unit, and produces a single wavelet at the D sandstone horizon. Initial seismic modeling indicated that the amplitude of the D sandstone event would be the primary indicator of reservoir-quality sandstone. Ten seismic attributes were picked and analyzed to develop an improved correlation technique. The seismic attribute correlation was used to update the estimates of OOIP made in 1988 and used in the original proposal. The new OOIP estimate is 6,900,000 bbl of oil for the D sandstone, approximately 1 million barrels higher than the original estimate. More significantly the seismic attribute correlation method was able to demonstrate a pattern of distribution and predict where to drill for compartmentalized oil.

The Sooner Unit project was the first 3-D seismic survey in the Denver Basin for exploitation of the D sandstone interval. The 3-D survey imaged the narrow and sinuous reservoir patterns of the fluvial and estuarine environment. The functionality of the seismic images was confirmed by pressure transient tests, which indicated bi-linear flow and channel widths averaging 600 ft. Functional reservoir compartments were found to average 80 acres in size with a major axis of one-half mile and a minor axis of one-quarter mile.

The cost of 3-D seismic for the Diversified project as $250,000 which was equal to the cost (in 1995-6) of completing a single well in the Sooner Unit. Significant cost savings can be realized by use of this seismic attribute technology in predicting drilling locations and avoiding dry holes.

As the result of this field demonstration project, 13 new seismic surveys have been shot in the D sandstone in nearby reservoirs. The 3-D seismic data and technology has been made available through the PTTC regional office in Golden, Co.

- **Cross-well Seismic for Enhanced Oil Recovery**
  Chevron, Buena Vista Hills Field and Lost Hills Field, Kern County, CA

Chevron has accomplished several "first's" in their seismic modeling and reservoir characterization of Buena Vista Hills and Lost Hills fields prior to implementing a CO_2 flood.

First high-resolution crosswell reflection images obtained in any oil field in the San Joaquin Valley were obtained using TomoSeis acquisition system at Buena Vista Hills in-------.

As part of this project, Stanford University developed improved velocity imaging algorithms, which will properly handle well deviations and will estimate small amounts of elastic anisotropy. Stanford is also developing improved reflection imaging algorithms, which can handle well deviation, elastic anisotropy and complex structure.

Interpretations from the TomoSeis survey have been published through the project and Stanford, and are available to other field operators in the San Joaquin Valley.

The crosswell seismic in was used in conjunction with other data to determine and map the oil saturation as Buena Vista Hills and determine that field was not a good candidate for CO_2 flooding. Similar analysis was applied to reservoir characterization of Lost Hills field prior to its selection for the CO_2 demonstration, which was implemented in June 2000.

- ## Cross-well Seismic and Seismic Attribute Analysis
  OXY, West Welch Field, Dawson County, TX

  3-D seismic integration improved the history match over the base geologic model results. Evaluation of the seismic responses led to the development of a statistical relationship between pore volume and seismic attributes. Five new wells were drilled based on seismic attribute guided mapping of porosity zones. The crosswell seismic identified a rock type that was not believed to be very extensive in the reservoir based on previous geologic data.

  Seismic has also been used in monitoring the movement of the CO_2 flood. Advanced Reservoir Technologies Inc developed a method for using core data at two central wells to calibrate the interwell seismic data to porosity, using the Biot-Gassmann equations. Statistics derived from the interwell data provide an alternative to analog measurements on outcrops. This is the first use of interwell seismic data for this purpose. The first CO_2 monitor surveys, which have been recently acquired, suggest a strongly directional flow pattern for the injected CO_2. The crosswell seismic data provides data on the migration and distribution of 60,000 barrels of CO_2 injected since 1997.

Technical information about technologies and projects described above are available in: ADD REFERENCES to NGOTP, fact sheets, success stories and validation sheets (as a group, not specific for each project)

b) Have produced technologies with the potential to be commercially viable in the mid-term (5-10 years) and why these technologies are viewed in this category. What was the DOE's role in the development of these technologies?

- ## Seismic Computational Techniques - Salvo
  Industry/National Lab Partnership, Sandia National Labs

  Salvo is a code that produces higher quality seismic images than traditional methods. Salvo's algorithmic improvements, designed to use the power of massively parallel computers, result in time savings between 10% and 40%, compared to other programs. Salvo will replace the current primary algorithm, Kirchhoff algorithm, used by the oil industry for 3-D imaging. Researchers have discovered that the Kirchhoff algorithm does not image complex structures to the degree of accuracy than they now require; multiple arrivals present a particular difficulty. Salvo was released to project members in October 1996, and preliminary results are promising.

  Partners with Sandia National Laboratories include: ARCO Oil and Gas, Conoco Inc., Cray Research Inc., Golden Geophysical Corp., IBM, Intel SSD, Oryx Energy Co., PGS Tensor, Providence Technologies Inc., TGS Calibre Geophysical, and the University of Texas, Dallas.

A typical marine seismic survey dataset can contain over 10 metabytes of data for each shot and over 1 terabyte of data for the whole survey. The time required to read the initial seismic data, read the velocity models , and write the images can be substantial, creating an input/output bottleneck. In Salvo, the input is performed by a subset of available nodes assigned to handle the I/O. The remaining nodes perform the pre-computations in the background, thereby mitigating the I/O bottleneck by performing preliminary computations and data redistributions using nodes not directly involved in the I/O. The trace dataset is distributed across many disks to increase the total disk to memory bandwidth.

To validate Salvo, tests were performed to ensure accurate imaging of reflecting layers. The 3-D SEG/EAGE salt model is an example of a Salvo migration. This synthetic model with synthetic receiver data is available through the SEG home page at
http://www.seg.org/research/3Dmodel/SALTHOME/segsalt.html

In 1999, researchers that have developed the algorithms won an R&D 100 Award in the annual competition for innovative technology sponsored by R&D Magazine.

- ## Seismic Modeling Techniques, Advanced Computational Tools Using the SEG/EAGE Model Dataset
  Industry/National Lab Partnership
  Los Alamos National Laboratory and Oak Ridge National Laboratory

The Elastic Modeling Initiative is calculating synthetic elastic data from a portion of the SEG/EAGE salt model, providing substantial new insights into important features of seismic wave propagation through the complex structures that oil and gas will be produced from through the next 5–10 years.

The synthetic seismic data that were computed from the SEG/EAGE salt model contain only "acoustic" wave effects. That means that the data contain only compressional waves. Current exploration often involves areas in which there are large changes in seismic velocities, such as areas of the Gulf of Mexico that include salt bodies, which can have compressional wave velocities that are twice those of the surrounding sediments. Such large contrast in seismic velocities can produce efficient conversion between compressional and shear waves. This is referred to as converted or elastic wave propagation.

The Elastic Modeling Initiative was started in response to industry concerns that elastic wave effects are not adequately understood, and that numerical modeling can give greater knowledge of how elastic waves propagate in some exploration situations.

The importance of the Elastic Modeling Initiative is underscored by the increasing acquisition of multicomponent seismic data (such as from ocean-bottom cables). These multicomponent data provide excellent opportunities to record elastic and converted wave data. Another factor increasing the importance of elastic waves is the need for more reliability of reservoir models to achieve better recovery of oil and gas from existing reservoirs. Reservoir models must utilize all available seismic, log, and rock physics data. The acoustic response of simple structures is readily modeled, and examples are available for routine use in many practical applications. The elastic response of complex structures is harder to model and similar examples are not readily available.

- **Seismic Instrumentation**
  Geophone Tubing Array, Los Alamos National Laboratory (LANL)

The Fracture Mapping and Slimhole Geophone Array project goal is to make microseismic fracture mapping routine. Downhole micro-seismic mapping and vertical seismic profiling (VSP) surveys in oil and gas reservoirs require costly well preparation and extended instrumentation deployments. Preparation of wells for deployment typically includes removal of tubing and installation of bridge plugs. Other costs include delayed production and returning the well to production. Through-tubing tools will significantly reduce costs of well preparation and return to production.

In 1993, successful through-tubing operations were demonstrated at Prudhoe Bay in Alaska. LANL fielded geophone tools for monitoring microseismicity where the cost of pulling tubing would be prohibitive. LANL's geophone tools, modified for through-tubing operations in pressurized, inclined wells, were deployed through 4-1/2 inch production tubing. An abundance of seismicity, both background and stimulation induced, with an acceptable signal-to noise ratio was observed.

A second use of the geophone was in the massive hydraulic fracturing project conducted by Exxon in the Austin Chalk at Giddings field. Exxon desired a seismic confirmation of drainage volume showing what areas of the reservoir were being contacted by hydraulic fracturing. Fracture location, aerial extent, and vertical containment can be determined by mapping microeathquakes induced during injection. Mapping was able to read the process zone extending nearly 1 km from the injection well. The reflected arrivals allowed the hypocenter depths to be determined accurately and indicated that the injection was contained within or near the productive interval at the base of the Austin Chalk.

A third use of the geophone seismic mapping technology was in Clinton County, Kentucky. To map reservoir fractures, production-induced microseismicity was monitored at three sites near new, relatively high-volume wells producing from shallow, fractured carbonate reservoirs in south-central Kentucky. High quality wave forms were recorded and mapped using only two or three downhole geophone tools.

- **Seismic Instrumentation, MEMS Accelerometer**
  Los Alamos National Laboratory (LANL)

The micromachined accelerometer (MEMS) is a member of the class of microelectromechanical systems. As part of the partnership project, Mark Products developed miniature (0.39 inch diameter) vertical and horizontal geophones. LANL designed, fabricated, and successfully tested a wireline-deployed package for the testing and evaluation of miniature accelerometers, geophones, and hydrophones. These sensors were field tested at Amoco, LANL, and Texaco borehole facilities.

Two 2-level, 3-component seismic arrays based on the successful prototype were designed and tested by LANL capitalizing on the MEMS sensors technology. In benchtop testing of the prototype, the MEMS pod qualitatively exhibited sensitivity comparable to a commercial geophone. The redesign reduced the complexity of each pod and streamlined the assembly into an array. Included in the redesign were: Improvements in the reliability of the locking arms; specially designed and fabricated feed-thru and connectors to accommodate up to 41 electrical conductors; and, a flex board circuit to pass power and telemetry through the electronic assemblies of each pod to the pods lower in the array.

The project also demonstrated that the arrays could be deployed and successfully retrieved and evaluated the potential contribution that data from microhole arrays contributed to seismic reflection surveying. A subcontractor to Phillips Petroleum collected 2D reflection data from conventional surface geophone arrays and two MEMS-borehole arrays. It is believed that this development represents the first reported use of MEMS technology for a borehole seismic array.

LANL has begun preparations with industry for the drilling of a 5000 ft microhole to demonstrate the capability to drill a deep microhole and obtain reservoir information using the microhole instrumentation developed under the Partnership funding.

ADD REFERENCES to NGOTP, fact sheets, success stories and validation sheet documents (as a group, not specific for each project)

c) **If the future results in a significantly increased energy price track than the current baseline forecast, or if some part of the conventional energy supply**

system should be curtailed for health or environmental systems, that would provide additional benefits.

This area is not applicable to seismic technologies.

FE 2. For each of the technologies identified, list and describe any products that resulted from DOE's R&D investment that are currently finding commercial or research application in an area other than the original project or program.

Seismic technology has the potential for numerous and unanticipated spin-offs but none are currently known.

FE 3. How would you suggest that the committee treat programs such as FE's waste characterization and toxic air pollution characterization activities?

This question is not applicable to seismic technology.

FE 4. How would you suggest that FE's advanced research program be treated in the study?

As this area generally deals with power systems, it should be included in the Coal and Power Systems input. This question is not applicable to seismic technology.

Section B

FE 5. For each of the technologies identified, what was the original justification for these technologies given to the U.S. Congress or OMB in the original project/program budgetary approval process?

Enhanced Oil Recover (EOR) field tests (conducted from 1976 to 1986) demonstrated that unpredicted reservoir heterogeneity was the dominant cause of technical or economic failure of EOR, leading both industry and government to conclude that improved interwell reservoir characterization was required.

Reservoir characterization and advanced instrumentation development R&D was initiated in the Advanced Process Technology (APT) and Enhanced Oil Recovery (EOR) programs in FY 1985. (The APT program focused on more basic and crosscutting R&D; whereas, the EOR program focused on reservoir characterization for application to improved oil recovery.) Seismic R&D, as part of reservoir characterization in both APT and EOR programs, was initiated in FY 1989 and the program generally has grown to the present time.

In FY 1989, the Oil Recovery Technology Partnership was initiated. In February 1989, representatives of Sandia and Los Alamos National Laboratories testified about the Partnership before the U.S. House of Representatives, Committee on Science Space and Technology, Subcommittee on Energy, Research and Development, stating that the DOE had created the Partnership to respond to the increasing dependence of the U.S. to foreign oil imports that put energy security at risk, reduce foreign policy options, and cause economic downturn in oil producing regions of the U.S. The testimony stated that the purpose of the Partnership was to provide the oil industry, especially independent operators, with a mechanism to access National Lab expertise, equipment, facilities and technologies that could have near-term applications in improved oil recovery processes. Consistent with industry guidance, the Partnership identified crosswell seismic as a strategic technology.

FY 1991 budget request was based on 1990 DOE publications – *Hydrocarbon Geoscience Research Strategy* and *Oil Research Program Implementation Plan.*

The *Hydrocarbon Geoscience Research Strategy* (DOE/FE-0186P) noted that domestic oil and gas production is critical to maintaining our national energy and economic security and geoscience research can enhance the naturally declining domestic production. Two-thirds of all oil and one-third of all gas will remain in known reservoirs after conventional production. As wells are abandoned economic access to these resources becomes more limited, creating an urgency to act quickly to preserve the economic viability of these fields. The DOE goal to increase the economic producibility of domestic oil and gas resources through geoscience research and related activities. Near term objectives (yielding results in five years) are to maintain economic access to currently producing domestic fields and decrease the rate of decline by application of currently available technology. Mid-term objectives (up to ten years) are to maximize oil and gas recovery through improved understanding of the resource and development of advanced extraction techniques, increasing the efficiency of resource discovery and expanding environmental understanding to keep pace with extraction technology. Long-term objectives (beyond ten years) are to improve the fundamental understanding of the oil and gas resource and support the community of scientists and researchers in the field of oil and gas discovery and recovery. Included in the strategies to achieve the mid-term objectives was development of advanced instrumentation, computation and interpretation techniques to locate and measure the resource and reservoir heterogeneities, e.g. seismic. A long-term strategy was development of subsurface imaging to map rock properties at reservoir depths with a resolution of one meter.

The *Oil Research Program Implementation Plan* (DOE/FE-0188P) provided details on the implementation of the Strategy, specifically: field demonstrations of currently available technology would address near-term objectives; field demonstrations of advanced technologies would address mid-term objectives; and, long-term objectives would be met by supporting research, including high resolution seismic instrumentation and advanced interpretation techniques.

In the FY 1995 CRB, DOE requested funding to initiate the Advanced Computational Technology Initiative for adaption and transfer to industry of National Lab high performance computational technology developed for defense purposes. This new program was defined in a 1994 publication.

The *Advanced Computational Technology Initiative* (1994, DOE/FE-0308P) aimed to "enhance, apply and transfer technologies developed within the National Laboratories to...increase the ability of domestic producers to find, recover, and process natural gas and oil at lower cost with reduced environmental risk." Geophysical imaging (2-D and 3-D seismic data acquisition, processing, and interpretation) was identified as a major focus. The program was designed, to function like the Natural Gas and Oil Technology Partnership Program, funding projects identified as high priority by industry.

FE 6. What was the total cost of the DOE R&D budget (in constant 1999 dollars) for each year 1978 to 2000? Provide the total budget for each of the technologies/projects identified on an annual basis (in constant dollars).

Table1: Seismic R&D budget by year, stated in 1999 dollars.

Year	Oil Program R&D Budget 1999 $000[3]	Oil Program Seismic R&D Budget 1999 $000 DOE[2]	Cost Share	Seismic Overhead 1999 $000 [1]
1978				
1979				
1980				
1981				
1982	31,900			
1983	17,500			
1984	20,720			
1985	24,432			
1986	24,546			
1987	20,221			
1988	26,030			
1989	34,905	1,727	0	136
1990	41,047	1,729	242	112
1991	60,425	1,847	518	91
1992	74,617	2,751	968	115
1993	75,070	12,349	10,519	981
1994	93,589	11,158	15,308	741
1995	94,480	38,181	20,219	3,175
1996	64,073	4,592	41,087	658
1997	52,486	7,922	4,803	901
1998	54,673	3,874	4,667	350
1999	47,348	5,336	6,310	537
2000	56,397	14,020	4,141	1,254

1: Prorated Overhead
2: Includes total project costs of class projects where seismic has significant contribution. Actual expenditures for seismic research, acquisition, processing, and interpretation can not be disaggregated, but may average about 20 percent of total project costs.
3: Historic program costs converted to 1999 dollars using REFERENCE?. A 2 % rate of inflation is assumed for post-1999 dollars.

FE 7. For each year from 1978 to 1999, for each of the technologies identified: what was the cost of DOE R&D support (in constant 1999 dollars); what cost-sharing arrangements with industry (or universities, etc.) were in place (amount to be specified); what proportion of the budget was spent:

(a) in direct performance contracts with industry; other federal, state, or local government agencies, or educational institutions
(b) in allocations to the national laboratories for in-house work;
(c) in allocations to the national laboratories for in-house work for external performance, and
(d) in overhead and support contracts.

Table 2: Allocation of Oil Program Seismic R&D budget among industry, other government agencies and academia; national laboratories; and, overhead and support contracts.

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Industry, Govt, & Univ												
DOE	251	238	0	0	81	978	253	229	492	389	714	6,895
Cost Share	0	242	0	0	0	0	0	0	0	64	150	2,598
National Labs (in house)												
DOE	1,476	1,491	1,847	2,751	2,436	2,332	4,784	1,606	3,850	2,795	3,622	3,587
Cost Share	0	0	518	968	834	6,445	10,417	262	0	3,449	6,160	0
Overhead & Support Contracts*	136	112	91	115	981	741	3,175	658	901	350	537	1,254
Reservoir Class & Class Revisit												
DOE					9,832	7,848	33,145	2,757	3,580	691	1,000	3,537
Cost Share					9,685	8,864	9,802	40,825	4,803	1,153	TBD	1,543

*Overheads are prorated for seismic program budget

FE 8. For each of the identified technologies, what factors influenced the DOE R&D annual funding allocations for each technology (both increases and decreases)? What external factors influenced these decisions (i.e., policy issues, administration changes, OPEC, etc.)?

Seismic R&D was initiated in FY 1989 as part of the APT and EOR programs. The FY 1989 CRB stated that Fossil Energy R&D would focus on coal, based on the fact that coal represents 80 percent of domestic fossil reserves but only contributes 23 percent of energy consumption. Consistent with this, APT budget request ($2.2 million) was 40 percent below the prior year appropriation and APT geoscience research was cut in half; however, the EOR request was level and EOR geoscience research was increased $2.1 million.

The FY 1991 budget request for the EOR and APT Programs proposed a $10 million initiative in the EOR, Light Oil Prgram for oil and gas recovery and geoscience research with consortia of states, universities and industry. In connection with funding this new initiative, Light Oil Program geoscience research was cut $5.3 million. The FY 1991 appropriation for consortia work in EOR Light Oil Program was over the request, $12 million, and funding requests and appropriations for cost shared field demonstrations continued to grow through FY ------. Consistent with the shift to more near- and mid-term demonstrations, basic or longer-term geoscience research including seismic generally declined through the same period.

The Energy Policy Act of 1992 states that it is a goal of the U.S. in carrying out energy supply and conservation research and development to strengthen the national energy security by reducing dependence on imported oil and instructs the DOE to conduct a five-year Enhanced Oil Recovery R&D program that is essentially the same program defined in the *Oil Research Program Implementation Plan.* FY 1992 through FY 1996 CRBs contain growing requests for funding for field demonstrations in high priority reservoir classes. Many of the field demonstration projects contained a significant component of seismic R&D. During this same period seismic research separate from the field demonstrations also increased slightly.

The FY 1995 CRB proposed an Advanced Computational Technology Initiative (ACTI) to transfer Defense-developed high performance computing technology to the gas and oil industry to enhance productivity in the areas of reservoir characterization, stimulation, and performance prediction, which minimizing the environmental impact of production ($10 million).

FY 1995 reorganization ended the Enhanced Oil Recovery and Advanced Process Technology Programs, merging them into the Oil Technology Program, part of the Natural Gas and Petroleum Technology Office. This reorganization was intended to make the DOE R&D program organization more consistent with that of the petroleum industry.

In FY 1996CRB, the oil program requested a budget 6 percent over the prior year, including a 15 percent increase in exploration and production supporting research and a 16 percent reduction in field demonstration funding. The actual appropriation was 40 percent below the oil request. The cuts were primarily directed to the field demonstration program and reservoir characterization research actually increased significantly over FY 1995. The National Lab partnership and ACTI funding dropped from almost $10 million in FY 1995 to $4.7 million in FY 1996.

FY 1996 through FY 2000 budgets for seismic R&D have been generally low, consistent with the Administration goal to keep budgets within the balanced budget agreement with Congress.

FE 9. For each of the technologies identified, qualitatively describe what would have happened in this area had there been no DOE role. What is the base case you assume over a 10 year period from the date the first DOE R&D funding began?

Significant ramp-up in the seismic technology area by the DOE-FE Oil Program began about 1988. Prior to that time, industry had substantial in-house investments in R&D and they preferred DOE to fund mainly long-term, high-risk RD&D type projects. All that changed around 1986 with the economic misfortunes the petroleum industry encountered due to price instabilities. Industry subsequently has been undergoing profound change and realignment, continuing even to today, in order to remain competitive and economically viable. Some of the changes industry has experienced are significant reduction of R&D dollars, closing of numerous research facilities, massive layoffs of technical and research staff, and a shift of what little in-house research that remains toward very near-term, project-support type efforts. This has necessitated numerous paradigm shifts within industry, such as; a willingness to collaborate on R&D projects in terms of staff and monies to leverage reduced budgets; look outside their parent organizations to tap technical expertise, thus an increased interest in the National Laboratories and academic consortia; encourage the petroleum service industry to "pick up" some of the needed R&D activities that will result in commercially available services; and outsource significant amounts of technical and research activities that prior to this time, industry would have completed in-house and held proprietary.

Within DOE, the results of a series of enhanced oil recovery demonstration projects conducted during the 1970's indicated that the lack of significant reservoir characterization activities prior to the fielding of demonstration efforts often doomed the overall effort. Increased emphasis and funding in reservoir characterization, including seismic tool and technologies development, was initiated in the 1980's.

The Natural Gas and Oil Technology Partnership (NGOTP) was formed through a DOE-FE Oil Program initiative in 1988 as a mechanism to address R&D needs within the context of the institutional realities faced by both industry and DOE. The NGOTP is a mechanism for collaborative R&D efforts between the DOE national laboratory researchers and the oil industry and supporting service industry. The industry driven program establishes active industry interfaces through review panels and forums that define industry needs, provide annual project reviews, and determines the priority of new proposals and ongoing projects. The growing interest and involvement of the U.S. industry (independent producers, service companies and majors) in the Partnership stems from their direct influence on the partnership principles. The Partnership has evolved from two laboratories working on four projects with four industry partners in 1988, to nine laboratories working on forty-five projects in all technology areas with over two hundred industry partners in FY2000.

DOE involvement with industry, through the partnership has aided the acceleration in seismic technology advancements in the areas of timing, cost and access. The DOE-FE Oil Program, with relatively small investments in R&D dollars, has acted as a facilitator to help drive advances in the evolution of seismic tools, technologies, and software. Some of the resulting advances would either never have occurred or would have been slowed considerably. Without the collaborative and cost-shared efforts, each individual company would have been forced to use scarce resources (if available) and often duplicate efforts, as each company would have considered their R&D advances in seismic technologies as proprietary. Through the use of Federal dollars, resulting seismic technologies are available to independent producers, who otherwise could not afford to invest the resources to gain access to these state-of-the-art tools. The increases in rates of successful exploration and development well completions and the additions of oil and gas reserves, particularly in the offshore Gulf of Mexico, would have been subdued in comparison to what is report earlier in this document.

FE 10. For each of the technologies identified, what were the original goals and objectives employed for these technologies, and how did these change throughout the duration of the project? What were the milestones that were used, and to what extent were these milestones met? What were the principle factors that influenced the changes in goals and objectives over time?

The original goal of seismic R&D was to improve seismic acquisition, processing and interpretation technologies to provide increased resolution and accuracy, with an emphasis on single-well, crosswell, and novel surface methods. The objectives were to; 1) increase discoveries of new domestic oil and gas fields, 2) increase U.S. oil and gas reserves, 3) increase success ratios for exploration and development wells thus reducing overall costs and impacts on the environment (fewer wells needed to extract the resource by more effectively targeting well locations), 4) Aggressively transfer the resulting seismic tools and technologies to the oil industry - independents, majors and service companies.

The DOE-FE Oil Program initiated the Natural Gas and Oil Technology Partnership (NGOTP) as a mechanism through which DOE could receive input from industry as to priority R&D needs, evaluation of proposed research activities and prioritization of research effort. The Crosswell Seismic Forum was one of the first forums under the NGOTP and industry participation directed R&D efforts toward development of tools (downhole sources and receivers) and algorithms to increase interwell reservoir image resolution for detailed reservoir characterization. In the late 1980's much of the onshore focus by industry was the identification and booking of additional reserves from known oil and gas reservoirs.

The industrial technical members of the Crosswell Seismic Forum meet every year to discuss program direction, evaluate R&D proposals presented by collaborative national laboratory and industrial participants, and offer suggestions as to priorities based on overall goals. All Forum projects are evaluated each year and the industrial members recommend to the Partnership office whether each project should be continued, terminated, combined with other projects, new projects that should be initiated, and relative order of project priority based on technical merit. As a result of these interactions, DOE can react quickly to promising new technical directions identified by the industry participants. In 1994, the Forum was broadened to include single-well imaging and thus the name was changed to Borehole Seismic Technology in response to industrial guidance. New projects were initiated in single-well imaging to improve seismic resolution around such features as salt domes using one well for both sources and receivers. In 1997 the Forum was broadened further to Diagnostic and Imaging Technology so that additional areas may be included such as development of algorithms for improving the resolution of subsalt imaging. These changes were a result of industry identifying new high priority R&D needs and matching these needs with national laboratory capabilities.

Numerous individual project milestones have been met as evidenced from the above discussion of selected tools, technologies and algorithms that have been developed through DOE cofunded R&D activities currently being commercially used by the industry. The rate at which these products are commercially fielded is a direct function of the technical complexity of the R&D effort, the level of funds available (from both DOE and industry), the level of effort by a oil service company to manufacture and field the resulting tool or technology, and the priority placed on the specific project by the Forum industrial reviewers. As can be seen by comparing the seismic program goals with the oil and gas reserve additions and increasing rates of exploration and development well completions, mentioned above; DOE has been successful in meeting its overall objectives. Not all the improvements in reserves and well completions can be attributed to DOE activities, rather it is a summation of the combined technical advancements made by industry, academics and government in the broad area labeled as "seismic" as well as other technical areas that has resulted in the collective successes. The paradigm shifts that both industry and government have been forced to go through over the past ten years, however painful, have required us to become more efficient and the acceleration of technical advancements has helped to meet that challenge.

FE 11. What were the outcomes of DOE R&D Support? (recognizing that this might be expressed as a monetary value; as number of units deployed; as degree of market penetration of some technology; as an intellectual contribution unable to be given a monetary value, etc>0 In particular, specify what contribution DOE R&D made in the context of the entire R&D effort, i.e., with explicit recognition of the contribution made by other participants.

Economic Benefits: include increased value of economically recoverable resources; reduced cost of finding and extraction; reduced life cycle costs of energy services; value of intellectual capital; and value of technology exports.

Environmental Benefits: include reductions in emissions; reduced costs of remediation; reduced impacts on biota; and reduction in use of toxic materials.

Seismic technologies have many impacts on environmental qualities associated with oil and gas operations. Seismic applications that more accurately define the reservoir improves overall environmental qualities as follows:

- Reduces dry holes – In exploration, seismic improves the success rate for discovering new reserves as fewer dry holes are drilled. Development drilling is also improved as fewed dry holes are drilled in delineating the reservoir boundaries and in infill drilling within the structure. Each dry hole damages surface environments, provides seepage avenues to contaminate aquifers or other zones, and develops wastes (cuttings, fluids, NORM, etc.) that must be disposed of properly.

- Reduces development wells – Seismic allows the operator to better plan development wells to take advantage of geological variations or fluid flow variations. This reduces the total number of development wells required and improves overall recovery.

Security Benefits: U.S. economic strength and security depends on a secure source of reasonably priced oil – oil provides 97 percent of transportation fuels. Oil consumption will continue to increase through 2020 despite energy efficiency improvements and use of renewable energy. Advanced technologies are necessary to slow the decline in domestic oil production and diversify U.S. sources of supply.

Energy security is vastly improved by operators using appropriate seismic technologies because seimic technologies improve overall oil recovery from assisting in better exploration success through extending the life of marginal wells. Each production area will increase their relative volumes of produced oils over time. In fact:

- Exploration success improves to include finding smaller, yet profitable, reservoirs than routinely possible,
- Developmental success improves such that more wells can be drilled to produce the resource faster and more efficiently, and
- Reduced costs and more effective recovery will lengthen the well's economic life to recover more oil.

FE 12. Provide a list of terminated DOE R&D programs in the period from 1978 to 2000 and the reason(s) for their termination.

University Research Program in geoscience, chemical EOR, and reservoir diagnostics – (1987) Program to develop fundamental knowledge in the applicable areas. Terminated due to de-federalization of oil research at the Bartlesville facility and transfer of efforts to NIPER.

ACTI program was terminated in ----- due to ------

FE 13. To the extent possible, quantify the benefits discussed of DOE's R&D.

The National Petroleum Technology Office uses two methods to estimate quantitative benefits. The first is a validation program where completed projects are reviewed to determine their impacts and contributions. The second is forward-looking and attempts to estimate the future benefits of various projects and technologies. The forward-looking method is used for program planning and evaluation.

Validation of Completed Project Benefits:

This is presented as detailed success stories for completed research projects. About 45 success stories have been investigated and validated to define how the research has been utilized by industry and the extent of benefits the program can legitimately claim. About validation of 100 histroic projects, when completed in two years, will provide calibration for DOE's metrics activities in the future and provide accurate verification of program success. An examples validation summary sheet is shown below:

Table 3: Validation summary sheet for the Columbia Lamont-Doherty Project.

Project 15: Columbia Lamont-Doherty Project	
Project Timing	Start Date: 7/15/93 End Date:4/30/96 Duration: 33 months
Technology Area	Seismic; Fluid Migration
Problem	It has been hypothesized, but never proven, that fault systems are conduits for active oil migration.
Working Hypothesis	Test the concept that growth faults in the Gulf of Mexico are conduits through which the producing reservoirs are charged and that enhanced production can be developed by producing from the fault zone
Technology Change	4-D seismic technique that monitors oil, gas and water migration in reservoirs over time
Measures of Success	**Increased use of program products:** Two new technologies developed and commercialized – AKCESS a basin model and a 4-D seismic model. Western Atlas building 23 new seismic boats to acquire data. The Lamont 4-D Software has been proven in over 21 actual 4-D projects worldwide, resulting in over $100 million of additional oil and gas recovery. **Arrest overall decline in oil production by 2005:** Texaco drilled the Teal well that IP'd at 1600 bopd; Statoil spotted three new wells in Gulfaks, one producing at 6300 bopd. **Matching or exceeding the all-time historical rate of EOR by the year 2005:** Projected 10 % increase in recovery in Texaco's Vacuum CO2 project in New Mexico and Exxon's projected 10+ % recovery of OOIP in Cold Lake steam flood in Canada. **Increased participation of oil producers in technology transfer:** Lamont sold the technology for $2,500,000; plus $4,00,000 commitment for research to look at improving/extending the technology.
Economic Detail	Royalties at 15 %: Estimated value = $22,500,000 Taxes at 7.09 %: Estimated value = $10,635,000 Technology Sales: Actual value = $6,500,000 Reserve Additions: Actual reserves = 1,200,000 BO (Teal Well) EOR Production: Estimated value = 5,000,000 BO
DOE Investment	$9,730,000 (50 % of total investment)
Return on Investment	**Quantifiable:** >100 % Additional research funding from technology sales ($6,500,000) and Taxes and Royalties from Teal well production ($3,960,000) and over $100 million of additional oil and gas recovery **Future Potential:** In excess of $100,000,000 primarily from taxes and royalties (By 2010 50 % of all seismic will be 4-D)
Objectives Met?	Major growth fault drilled into, but production could not be established. Success in coring that introduced new technology and success in predicting the location of oil flow has promoted other fault zone tests by industry
Outcome	Fully Successful
Application (area/region)	Improve Reservoir Management Practices thereby producing additional reserves, EOR Projects, & Acquisitions in fields around the world
Limitations	Requires a seismic history. Legacy data will have many old 3-D surveys that cannot be compared with new surveys. Coupling between a reservoir simulator and a seismic simulator will require significant computer cycles. Acquisition and processing differences must be overcome by software or new sensor technologies (e.g. bottom cables). Techniques for the 4-D analysis of fields with subtle

	hydrocarbon indicators must be developed.
Recommendations	Continue development of the next generation of technology, 5-D seismic monitoring, in which sensors in the reservoir would allow real-time control of fluid flow, thus greatly enhancing the efficiency of the recovery process.

Estimation of Future Benefits of Current Program:

There is a growing need to effectively measure the outcomes and value of research programs. These estimates are not only good business practice, but for Federally-funded programs, they are mandated by statutes such as the Government Performance and Results Act of 1993 (GPRA). The development of benefit estimation forecasts of the Oil Program has been aided by the application of a consistent methodology, peer review of results, project validations, and creation of a PC-based software application to facilitate users in developing estimates. Our methods have been very successful in communicating the value of the DOE's oil research, setting priorities among projects and programs, and developing a baseline for project validation.

The seismic technology area includes seismic methods, field acquisition tools, data analysis algorithms and processes, etc. Benefit estimates in Table 4 were made for each separate grant or contract then aggregated for seismic technologies as a single unit, i.e. - Product 1.2 Seismic Tools and Analysis.

Critical parameters for the estimation process are developed by the Technical Managers and their staffs and include:

- The expected change, normally recorded as *percent change*, that a new technology will produce;
- The actual resource that will be impacted by the new technology;
- The number of years and funding required to complete research into the technology;
- The number of years needed to effectively commercialize the technology;
- Determination of the benefit as being either one-time or recurring — one-time benefits are those acting on a finite resource base; recurring benefits accumulate as often as the product is used;
- Ultimate market penetration, normally recorded as the percentage of the resource the technology will be applicable to;
- Estimation of the probability of success.

Two benefit estimates are actually developed, one for "Industry Only" and the other for "Industry + DOE." This is done so that advancements anticipated from industry-sponsored research are forecast as well as those from the DOE. This enables an easy comparison of DOE forecasts to national forecasts made by external industry organizations. Once validated, estimates provide annual estimates of benefits for a 20-

year period. Benefit estimates can be aggregated at any technology or programmatic level and are measured in several ways, e.g. dollars saved, production, reserves made economic, reduced dry holes, etc. The logic and data sources used to make the benefit estimates are documented. Documentation of the benefit methodology and supporting computer program is contained in: ADD REFERENCES to TORIS, OPRA, validation process, etc.

There has been increased acceptance and utility of DOE's oil research benefit forecasts. Forecasts have been used in high-level reviews of the program by DOE staff and the President's Committee of Advisors on Science and Technology.

Table 4: Cumulative future benefit estimates for FY1999 seismic R&D in DOE Oil Program.

DOE Oil Program – Seismic Tools & Analysis

7/25/00

DOE Net Contribution - Preliminary

Total Gas includes Associated Gas and Non-Associated Gas

Cumulative -- Crude Oil Production million barrels

Product Line.Product	2006	2011	2016	2021
1.2 Seismic Tools & Analysis - Development	37	66	91	117
1.2 Seismic Tools & Analysis - Onshore Exploration	184	328	451	481
1.2 Seismic Tools & Analysis - Offshore Exploration	139	248	340	363
1.2 Seismic Tools & Analysis - TOTAL	**360**	**643**	**882**	**962**

Cumulative -- Natural Gas Liquids Production Million barrels

Product Line.Product	2006	2011	2016	2021
1.2 Seismic Tools & Analysis - Development	13	24	33	43
1.2 Seismic Tools & Analysis - Onshore Exploration	53	94	129	138
1.2 Seismic Tools & Analysis - Offshore Exploration	46	83	113	121
1.2 Seismic Tools & Analysis - TOTAL	**113**	**201**	**276**	**302**

Cumulative -- Total Natural Gas Production, BCF

Product Line.Product	2006	2011	2016	2021
1.2 Seismic Tools & Analysis - Oil & Gas Development	256	1,011	1,754	1,906
1.2 Seismic Tools & Analysis - Oil & Gas Exploration	524	1,174	1,769	1,892
1.2 Seismic Tools & Analysis - TOTAL	**780**	**2,185**	**3,523**	**3,798**

Cumulative -- Millions of Dollars Saved

Product Line.Product	2006	2011	2016	2021
1.2 Seismic Tools & Analysis - Dry Hole Cost Savings	148	542	1,184	1,722

FE 14. To what extent has EE/FE met the goals of its 1978, 1984, 1985 and 1994 strategic plans?

The FE Strategic Plan (1998) supports the Secretary's Strategic Plan and has as an ultimate goal to improve energy security by increasing domestic production by 500,000 barrels per day during the 2001-2010 time period. The Comprehensive National Energy Strategy (1998) states a goal to stop the domestic production decline by 2005. A budget is assumed in making these plans and reduction in these budgets affect FE's ability to meet the goals. With the reduction in budget experienced in the years since the plan, FE does not expect to achieve the production goals for the latest strategic plan.

Other plans, such as the 1989 *Federal Oil Research: A Strategy for Maximizing the Producibility of Known U.S. Oil* and the 1990 *Oil Research Implementation Plan*, assumed budgets to implement field demonstrations (including seismic reservoir characterization) in 10 classes of reservoirs (Reservoir class Program) to add about 76 billion barrels of oil to our domestic reserve base. Funding was terminated after 3 classes of reservoirs were initiated. The first 3 classes represent a large proportion of all U.S. reservoirs, but the ultimate goal will not be achieved. The Reservoir Class Program is hailed as a great success even with its curtailed implementation.

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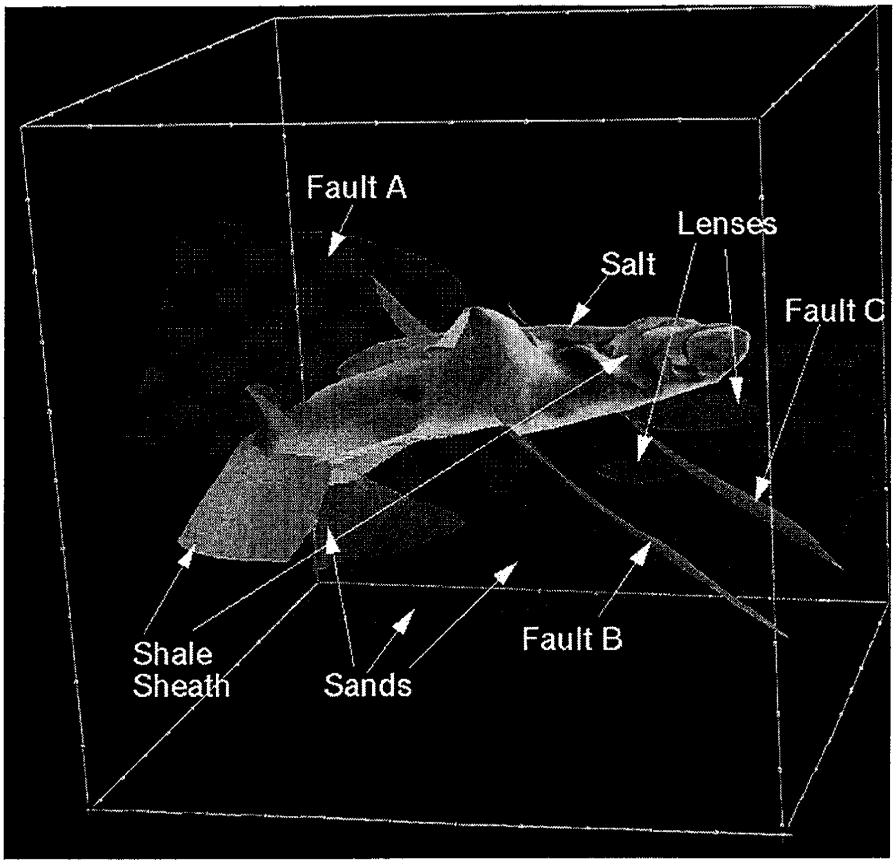
SUPPLEMENT 1

U.S. Department of Energy
Office of Fossil Energy
National Petroleum Technology Office

SEISMIC TECHNOLOGY



Sections FE-4 and FE-6

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FE 4. For each year from 1978 to 1999, what was the cost of the DOE R&D support for each of the technologies identified (in constant 1999 dollars). What cost-sharing arrangements with industry or other institutions were in place (total project lifetime constant 1999 dollar amounts). Organize by R&D stage of development (for example, basic research, applied R&D, demonstration, commercial deployment).

The tables below show the Seismic Technology budgets from 1989 to 2000. The budget tables are broken out by the major research performer. Research in these areas is both basic and applied research. There was no Seismic Technology program prior to 1989.

Table 4-1. Seismic Technology Funding Table

DOE FUNDING

Nominal Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	73	550	237	219	479	3	75	3,194	**4,830**
Universities/Colleges	200	197	0	0	0	348	0	0	0	380	639	3,839	**5,603**
National Labs	1,175	1,233	1,583	2,415	2,190	2,140	4,486	1,535	3,751	2,755	3,622	3,659	**30,544**
Class & Revisit	0	0	0	0	8,840	7,203	31,083	2,635	3,488	681	1,000	3,608	**58,538**
Annual Totals	**1,375**	**1,430**	**1,583**	**2,415**	**11,103**	**10,241**	**35,806**	**4,389**	**7,718**	**3,819**	**5,336**	**14,300**	**99,515**
Cumulative Totals	**1,375**	**2,805**	**4,388**	**6,803**	**17,906**	**28,147**	**63,953**	**68,342**	**76,060**	**79,879**	**85,215**	**99,515**	
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230	

1999 $ Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	81	600	253	229	492	3	75	3,122	**4,857**
Universities/Colleges	252	239	0	0	0	380	0	0	0	386	639	3,753	**5,647**
National Labs	1,478	1,493	1,850	2,755	2,440	2,335	4,791	1,608	3,855	2,796	3,622	3,577	**32,599**
Class & Revisit	0	0	0	0	9,848	7,860	33,196	2,761	3,584	691	1,000	3,527	**62,467**
Annual Totals	**1,730**	**1,731**	**1,850**	**2,755**	**12,369**	**11,175**	**38,241**	**4,598**	**7,931**	**3,876**	**5,336**	**13,978**	**105,571**
Cumulative Totals	**1,730**	**3,461**	**5,311**	**8,066**	**20,434**	**31,610**	**69,850**	**74,449**	**82,380**	**86,256**	**91,592**	**105,571**	

COST SHARE FUNDING

Nominal Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	0	0	0	0	0	0	87	781	**868**
Universities/Colleges	0	200	0	0	0	0	0	0	0	63	63	1,869	**2,195**
National Labs	0	0	444	850	750	5,915	9,769	250	0	3,400	6,160	0	**27,538**
Class & Revisit	0	0	0	0	8,708	8,135	9,192	39,025	4,679	1,137	0	1,574	**72,450**
Annual Totals	**0**	**200**	**444**	**850**	**9,458**	**14,050**	**18,961**	**39,275**	**4,679**	**4,600**	**6,310**	**4,224**	**103,051**
Cumulative Totals	**0**	**200**	**644**	**1,494**	**10,952**	**25,002**	**43,963**	**83,238**	**87,917**	**92,517**	**98,827**	**103,051**	
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230	

1999 $ Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	0	0	0	0	0	0	87	763	**850**
Universities/Colleges	0	242	0	0	0	0	0	0	0	64	63	1,827	**2,196**
National Labs	0	0	519	970	835	6,455	10,433	262	0	3,451	6,160	0	**29,084**
Class & Revisit	0	0	0	0	9,701	8,877	9,817	40,886	4,808	1,154	0	1,539	**76,782**
Annual Totals	**0**	**242**	**519**	**970**	**10,536**	**15,332**	**20,250**	**41,148**	**4,808**	**4,669**	**6,310**	**4,129**	**108,913**
Cumulative Totals	**0**	**242**	**761**	**1,731**	**12,267**	**27,599**	**47,849**	**88,997**	**93,806**	**98,474**	**104,784**	**108,913**	

TOTAL FUNDING

Nominal Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	73	550	237	219	479	3	162	3,975	**5,698**
Universities/Colleges	200	397	0	0	0	348	0	0	0	443	702	5,708	**7,798**
National Labs	1,175	1,233	2,027	3,265	2,940	8,055	14,255	1,785	3,751	6,155	9,782	3,659	**58,082**
Class & Revisit	0	0	0	0	17,548	15,338	40,275	41,660	8,167	1,818	1,000	5,182	**130,988**
Annual Totals	**1,375**	**1,630**	**2,027**	**3,265**	**20,561**	**24,291**	**54,767**	**43,664**	**12,397**	**8,419**	**11,646**	**18,524**	**202,566**
Cumulative Totals	**1,375**	**3,005**	**5,032**	**8,297**	**28,858**	**53,149**	**107,916**	**151,580**	**163,977**	**172,396**	**184,042**	**202,566**	
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230	

1999 $ Budgets (Thousand Dollars) - Seismic Technologies

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	SUM
Industry	0	0	0	0	81	600	253	229	492	3	162	3,886	**5,707**
Universities/Colleges	252	481	0	0	0	380	0	0	0	450	702	5,580	**7,843**
National Labs	1,478	1,493	2,369	3,724	3,275	8,790	15,224	1,870	3,855	6,247	9,782	3,577	**61,684**
Class & Revisit	0	0	0	0	19,548	16,737	43,013	43,647	8,393	1,845	1,000	5,065	**139,250**
Annual Totals	**1,730**	**1,974**	**2,369**	**3,724**	**22,905**	**26,507**	**58,491**	**45,747**	**12,740**	**8,545**	**11,646**	**18,108**	**214,484**
Cumulative Totals	**1,730**	**3,704**	**6,072**	**9,796**	**32,701**	**59,208**	**117,699**	**163,446**	**176,186**	**184,730**	**196,376**	**214,484**	

FE-6. For each of the technologies identified, fill in the matrix from the benefits framework. List separately any assumptions used in estimating the benefits of the R&D.

Table 6-1. SEISMIC TECHNOLOGY MATRIX SUMMARY

	Realized	Options	Knowledge
Economic Benefits/Cost	1989 to 2005 cumulative Total Program Benefit of $27,254 million; Public Sector Return of $8,317 million, and at a cost of $161 million, in 1999 constant dollars (see annual graph below) --- includes: • Incremental oil and natural gas production • Reduction in the number of wells needed to drain reserves • Reduction in the number of dry holes, exploration & development wells • Increased production from Federal lands and waters, including sub-salt and ultra-deep Gulf of Mexico (GOM)	2006 to 2021 additional cumulative Total Program Benefit of $20,793 million; Public Sector Return of $7,021 million in 1999 constant dollars (see annual graph below) --- includes: • Incremental oil and natural gas production • Reduction in the number of wells needed to drain reserves • Reduction in the number of dry holes, exploration & development wells • Increased production from Federal lands and waters, including sub-salt and ultra-deep GOM (see detailed background material)	Qualitative • Knowledge base of basic reservoir properties gleaned from seismic to target exploration and field development potential • Knowledge base of seismic acquisition, processing and interpretation • Tie 3-D/3-C and 4-D seismic more directly to reservoir rock and fluids distributions through attribute analysis to more accurately image the reservoir and high potential regions • Develop algorithms to increase processing efficiency-reduce computational and man-power costs (see detailed background material)
Environmental Benefits/Cost	Qualitative • Fewer wells drilled reducing potential surface and subsurface environmental impacts • Fewer dry holes drilled - reducing potential surface and subsurface environmental impacts • Reduced air emissions due to reduced power; lower fuel consumption and less drilling waste volume.	Qualitative • Target drilling/development activities to minimize environmental impacts in sensitive environments • Minimizing environmental impacts by more accurately determining foundation conditions for offshore facilities prior to placement • Reduced water production by better well placement and reservoir management	Qualitative • Near-surface and deeper seismic imaging may be applied to resolve environmental problems

	• Better field management by optimizing injection/production strategies through near real-time seismic monitoring of oil fields		
Security Benefits/Cost	Qualitative • Maintain domestic oil industry infrastructure through identification of untapped reserves in and around existing production allowing for increased production in time of crisis • Image new exploration and development potential within the U.S. to accelerate increased production in time of crisis, particularly in regions such as continental shelves, GOM and the North Slope of Alaska • Transfer technology to independent producers (increasingly important part of domestic production)	Qualitative • Project results provide a strong national knowledge base - captures technical expertise of domestic industry to improve efficiency and make it available to all of industry (CNES 1998 Goal IV, Objective 1, page 23) • Support of R&D through universities aid in developing and maintaining a highly educated, technically advanced work force	Qualitative • R&D and technologies will be used within the U.S. and throughout the world to increase both domestic and international oil reserves, further diversifying oil sources and international imports

FE Research Development and Demonstration Metrics

There are many products developed in our RD&D programs that can be included into any discussion on benefits/metrics. But, the major concept of benefits suggests that we measure what we produce. In that vein, this task would be easy. Fossil Energy produces RD&D. We develop our RD&D programs to solve specific, known problems associated with oil and gas exploration, development, and processing, and then prepare and manage procurements that end up as awards to companies, universities and other National Laboratories to do specific things to solve the identified problems. Our metrics would be how well we performed in planning and implementing these RD&D programs. Fossil Energy has performed in an excellent manner to plan and develop its RD&D programs. We have used portfolio analyses, roadmapping exercises, partnerships, feedback workshops, modeling systems to analyze programmatic options, industry meetings, peer reviews, and a myriad of other techniques to plan and organize our efforts –

always focusing upon our customers and the resource base we are trying to address. Fossil Energy is very successful in implementing its assigned RD&D program areas.

When review panels and others are tasked to review our benefits to the public, the first question is usually how much energy, be it oil, gas, or electricity, do you produce. The fact is that our control on how the RD&D performed in our programs is used is very limited. These limitations are centered upon our ability to contact our customers and influence them to use the new tools, techniques, technologies, or other products to increase energy recovery and availability.

In developing our planning tools, FE has developed modeling systems which allow us to estimate how much of the resource base may be affected by new technology development, upgrading of existing technologies, or simple efficiency gains in operations. Fossil Energy has also developed other supporting systems to be able to supply metrics to answer most of the questions being asked about benefits. There are, of course, many ways to estimate metrics and many programmatic parameters that could be considered. First and foremost, Fossil Energy is a government agency and not a producing company. Whenever a new product is developed, it is not applied only to a few properties that an individual company owns or operates. The new product is applied to the entire resource base that the new product may affect. While an individual company may expect rates of return of 10-20 percent for a new development, the government would expect many times this return as the product will be used by multiple companies on multiple properties. Therefore, the return on investment will be much higher than for an individual company. Other parameters that could be used to develop metrics are public sector revenues versus public sector investments, jobs created or maintained, environmental emissions reduced, efficiency gains in all aspects of petroleum exploration, production, and refining, and reduced costs attributable to the new products.

For this series of reports looking at the benefits of the Fossil Energy oil and gas programs, DOE will report both the economic activity (monetized production plus cost savings) and the Public Sector Return (Federal and state taxes, Federal royalties on Federal lands, and state production taxes). While both of these benefit measures are based upon the production of oil and gas, they are not similar. One is the value of production, while the other is the value of the production to the government.

Seismic Technology Issues

Seismic technologies are geophysical techniques used to image oil reservoirs, the associated rock and fluids from the earth's surface and/or from nearby wellbore. The application of seismic in oil exploration and development has increased ultimate recovery, reduced risk and costs by identifying barriers and pathways of fluids movement through the reservoir, thus allowing for more effective targeting of well placement and management of enhanced oil recovery projects.

Reductions in Finding Costs: Through the application of improved seismic technologies and increased efficiencies of operation, major oil companies have been able to reduce finding costs from $25 per barrel of oil equivalent to about $5 per barrel of oil equivalent for U.S. offshore operations and from $20 per barrel of oil equivalent to $5 per barrel of oil equivalent for U.S. onshore and foreign operations between 1981 and 1994. Finding costs again increased somewhat between 1994 and 1999 due to higher costs associated with Gulf of Mexico deepwater and subsalt activities, and because low oil prices caused downward revisions in "booked" reserve values. From late 1999 to date, overall finding costs for many major oil companies have tended to return to the $5 per barrel of oil equivalent baseline.

Increased Exploration and Development Well Success Rates: Seismic applications have evolved rapidly over the past twenty-five years, from mainly exploration (using 2-Dimensional and some 3-D) to exploration and development (using 3-D, 3-D/3-Component and 4-D [including time]) resulting in increased successful well completions rates. Exploration well success rates (for both oil and gas) have increased from an average 23% from 1973 to 1975 to an average of about 33% from 1994 to 1999. This represents a 45% improvement in only 25 years. Development well success rates have improved from an average of 78% to an average of about 85% over the same time period.

Increases in exploration and development well completion rates means that while fewer wells have been drilled between 1981 and 1998, considerably more oil and gas is produced per well, thus increasing recovery efficiencies. Oil production per successful oil well drilled per year during this time frame has increased by 330%. While the total number of successful wells needed to produce this oil have declined by about 84%, the overall decline in U.S. oil production during this period has only fallen by about 30%. The implication is that through the increased emphasis on seismic and other technologies over the past 20 years, industry has been able to become much more efficient in finding and developing oil and gas resources and thus slowing the rate of overall U.S. oil and gas production decline.

Increased Gulf of Mexico Deepwater Production / Proved Reserves: The application of three-dimensional (3-D) seismic imaging (today's leading imaging technology) in Gulf of Mexico exploration and development efforts has led the way to the revitalization of this important oil and gas prone region. The use of 3-D seismic has resulted in exploration well completion success rates doubling to 40 % between 1985 and 1994. Oil production from this region has increased by 39% between 1992 and 1998, to where the Gulf of Mexico presently provides about 16% of the total U.S. oil production and about 25% of the total gas production.

In 1998, 46% of the total Gulf of Mexico oil production and about 15% of the total Gulf of Mexico gas production was derived from the deep-water portion of this region. Oil reserve growth in deep-water U.S. Gulf of Mexico region has increased by almost one billion barrels between 1992 and 1998. Deep-water area gas reserve growth during the same time frame was 4.3 trillion cubic feet or a 130% net increase. The deep-water natural gas liquids proven reserves increased 42% during this same time period. Most of above proven reserve growth in this portion of the Gulf of Mexico can be directly attributed to improvements in seismic technologies and associated advancements in drilling, completion and production technologies directed toward these deep water reservoirs.

Subsalt Production and Proven Reserves in the Gulf of Mexico: It is estimated that up to 10 billion barrels of oil lie beneath the salt features in the Gulf of Mexico. There have been 13 successful exploration and development tests through mid-1998 that should add reserves to those of the Mahogany, Enchilada, and Gemini giant reservoirs (greater than 100 million barrels reserves) found through this process. This opens up potentially great reserves in reservoirs underlying salt deposits throughout the world.

Quantitative Benefit Estimation

We utilized several data sources, model results, and analyses, in a multi-step process to define quantitative benefits for the Seismic Technology Programs. Two estimates are presented in the graphs below. The first is Total Program Benefit. This is a measure of the value of all oil and gas production in the U.S. due to the DOE program and all cost savings. This estimate does not contain any tax or royalty revenue. The second estimate is the Public Sector Return. This is a relatively conservative estimate because the benefits of incremental oil and gas domestic production due to the DOE programs are measured as revenue that is returned to the federal, state or local treasuries and not the total value of the production. The major steps in these estimates are:

STEP ONE – Modeled or used actual project results for the benefit of new technologies.

STEP TWO – Identified the portion of the benefits attributable to DOE funded research and to Industry research. The benefits of all new technology are modeled using the Total Oil Recovery Information System (TORIS) and the Gas Supply Analysis Model (GSAM). Three unique estimated are modeled:

- No new technology,
- Industry technology only, and
- DOE and Industry technology from R&D

The incremental benefit of the DOE programs are calculated by subtraction of the Industry only benefits from the DOE+Industry benefits.

STEP THREE – Calculated gross benefits due to DOE research in categories of:

- Oil production
- Natural gas production
- Dollars Saved due to increased efficiency

STEP FOUR – Calculate the Total Program Benefits and Public Sector Return. A complete discussion of the modeling assumptions and procedures are contained in Appendix B.

Total Program Benefits:
Total Program Benefits are based on oil and gas production times oil and gas price tracks (uses Energy Information Administration (EIA) historical data and future year price tracks). In addition, Total Program Benefits include cost savings from improved efficiencies for exploration, production and refining operations.

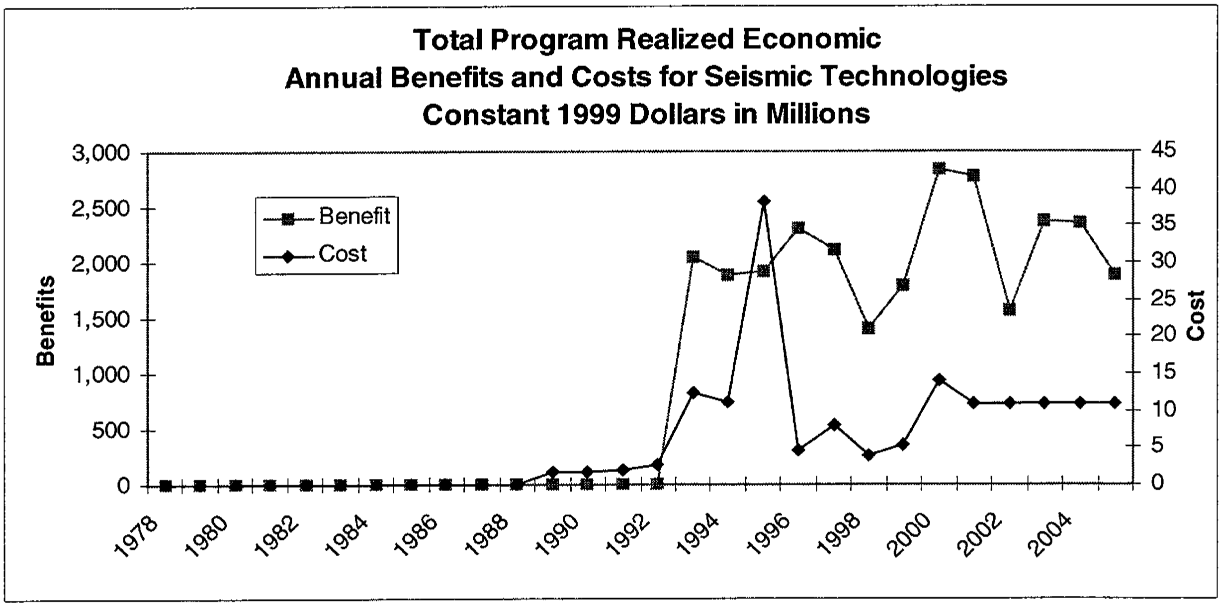
Public Sector Return Benefits:
The tax rates below are average rates based on TORIS modeling studies/results conducted in Tulsa, Oklahoma, by the National Petroleum Technology Office. These studies encompass more that 65% of U.S. oil production, and the average effective tax rates listed below are representative for domestic production. These are:

- Federal Tax 12.85% of total production value
- State Tax 1.90% of total production value
- Production and Severance Taxes 4.55% of total production value

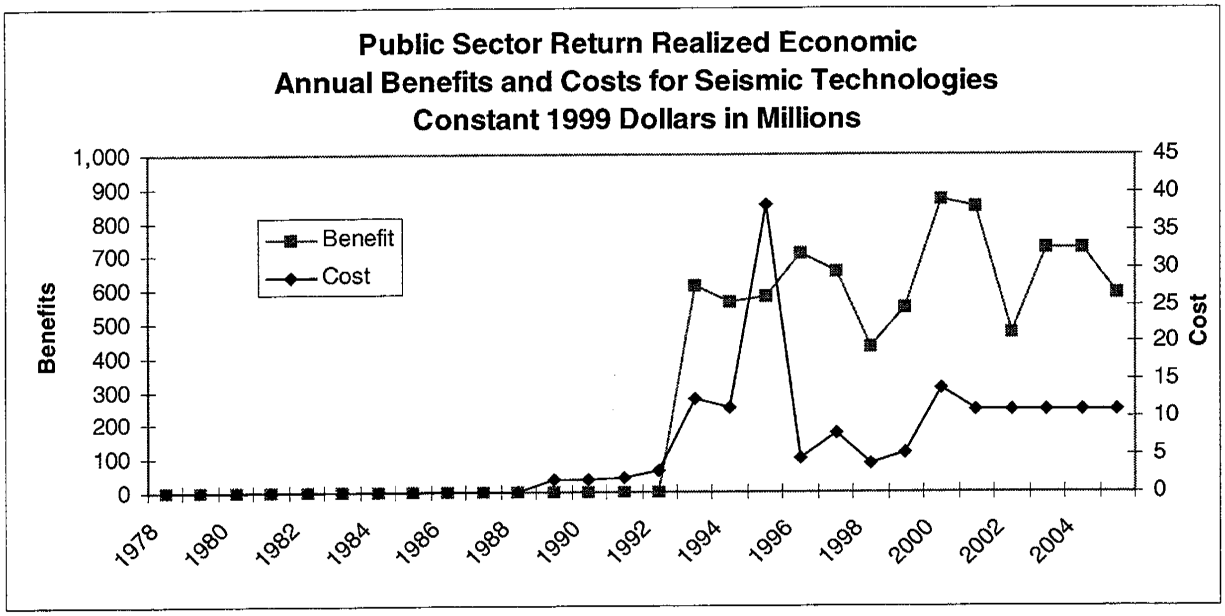
The above tax factors are applied to the economic value of the incremental production due to the DOE program. The product is then added to the Royalties from production on Federal Lands to determine the Public Sector Return. {Royalty rates for production from Federal Lands range from 13 to 16% based on Bureau of Land Management (BLM) and Minerals Management Service (MMS) historical data.}

Public Sector Return is then added to dollars saved from improved efficiencies for exploration, production and refining operations.

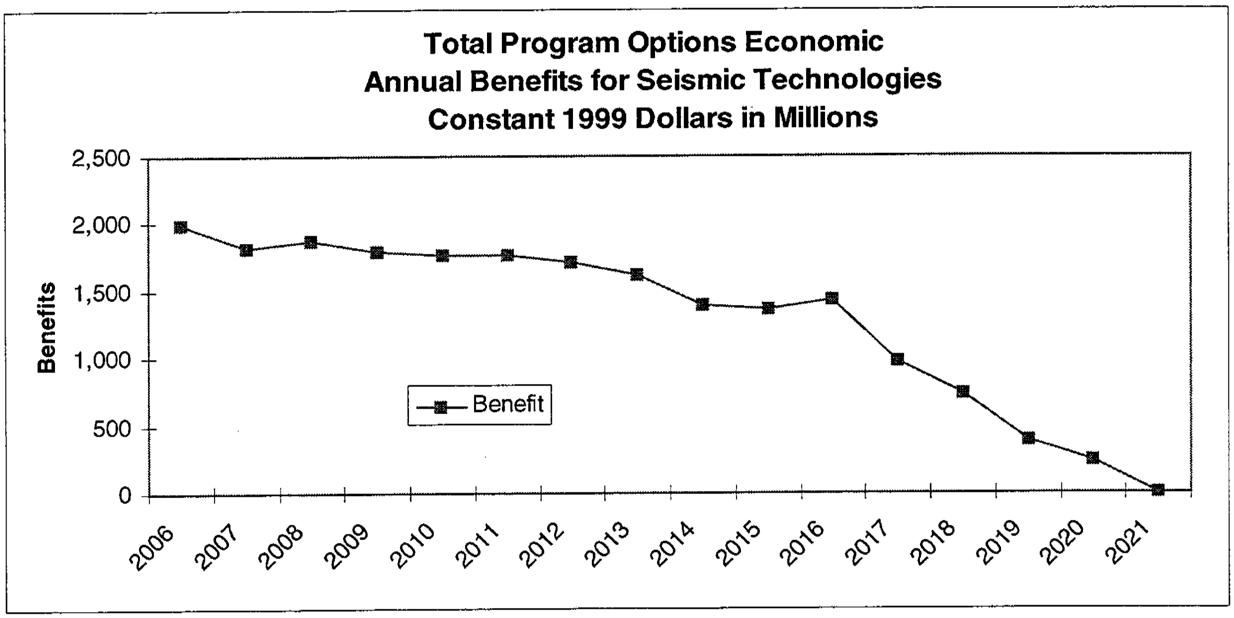
STEP FIVE – Convert the annual nominal dollar benefits to constant year 1999-dollar benefits.



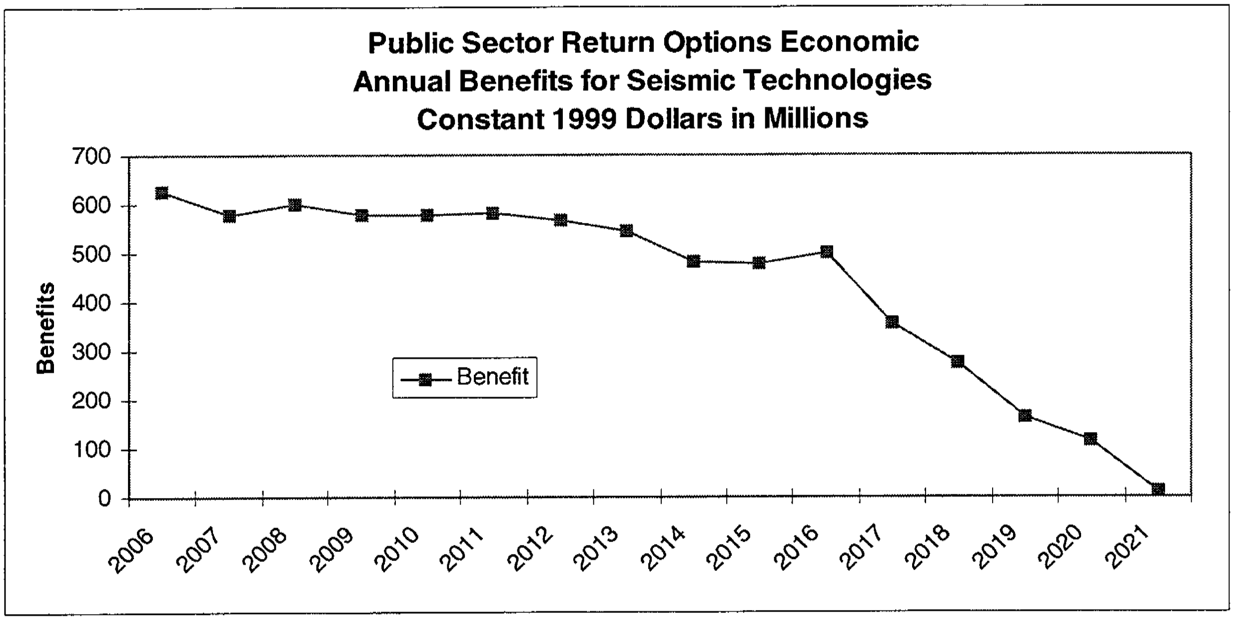
Graph 6-1. Total Program Benefit and Cost for the Seismic Technologies (1978-2005).



Graph 6-2. Public Sector Return and Cost for the Seismic Technologies (1978-2005).



Graph 6-3. Total Program Benefit for Seismic Technologies (2006-2021)



Graph 6-4. Public Sector Return for Seismic Technologies (2006-2021)

Table 6-1. Nominal Data for Realized Economic Benefits for Seismic Technology Programs.

The backup data in nominal dollars. Oil in million barrels, gas in BCF, dollars in millions.

Natl. Oil Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94	92	91	91	91	88	85	85	85	70	109	111	90
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94	186	277	368	459	546	631	716	802	872	981	1,092	1,182
Natl. Gas Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	181	188	186	189	189	187	187	196	196	87	147	167	171
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	181	369	555	744	933	1,120	1,307	1,503	1,699	1,786	1,933	2,100	2,270
$ Saved	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	25	25	25	25	24	24	24	24	10	20	30	39
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	125	149	173	197	221	231	251	280	320
Econ. Activity $	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,810	1,701	1,769	2,182	2,025	1,362	1,763	2,879	2,879	1,672	2,579	2,604	2,129
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,810	3,511	5,279	7,461	9,486	10,848	12,611	15,490	18,370	20,042	22,621	25,225	27,354
Public Sector																												
Return $	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	526	489	518	651	612	402	527	860	860	500	771	778	636
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	526	1,015	1,533	2,184	2,796	3,198	3,724	4,585	5,445	5,945	6,715	7,493	8,129
Federal Oil Prod	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	19	20	21	20	20	20	20	16	25	26	21
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	35	65	75	96	116	136	155	175	191	216	242	263
Fed. Gas Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	68	68	73	74	71	74	77	77	34	58	65	67
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	133	201	274	349	419	493	570	647	681	739	804	871
Fed. Royalties $	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	56	60	80	79	52	66	108	101	60	92	94	78
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	116	176	256	334	386	452	560	661	721	814	907	985

Table 6-2. Nominal Data for Options Economic Benefits for Seismic Technology Programs.

The backup data in nominal dollars. Oil in million barrels, gas in BCF, dollars in millions.																
Natl. Oil Prod.	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	92	79	81	73	69	69	69	67	63	59	56	44	32	19	12	0
Cumulative	1,274	1,353	1,434	1,507	1,576	1,645	1,714	1,782	1,844	1,903	1,959	2,003	2,034	2,054	2,066	2,066
Natl. Gas Prod.	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	208	229	256	285	315	321	303	282	213	238	301	165	128	39	17	-75
Cumulative	2,478	2,707	2,964	3,248	3,564	3,884	4,188	4,470	4,683	4,921	5,222	5,387	5,515	5,554	5,571	5,497
$ Saved	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	49	59	69	79	89	99	108	118	128	138	148	135	121	108	94	81
Cumulative	369	428	497	576	665	763	872	990	1,119	1,257	1,405	1,539	1,660	1,768	1,862	1,943
Econ. Activity $	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	2,287	2,117	2,235	2,162	2,184	2,219	2,188	2,104	1,834	1,831	1,965	1,344	1,004	508	299	-216
Cumulative	29,641	31,758	33,993	36,155	38,339	40,559	42,746	44,851	46,685	48,516	50,481	51,825	52,829	53,337	53,636	53,420
Public Sector																
Return $	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	683	633	668	646	653	663	654	629	548	547	587	402	300	152	89	-65
Cumulative	8,813	9,445	10,113	10,759	11,412	12,075	12,729	13,357	13,905	14,453	15,040	15,441	15,741	15,893	15,982	15,918
Federal Oil Prod	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	21	18	19	17	16	16	16	16	15	14	13	10	7	4	3	0
Cumulative	284	303	321	338	354	370	386	402	417	430	443	453	461	465	468	468
Fed. Gas Prod.	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	82	90	101	112	124	126	119	111	84	93	118	65	50	15	7	-29
Cumulative	953	1,043	1,144	1,256	1,379	1,506	1,625	1,736	1,819	1,913	2,031	2,096	2,147	2,162	2,169	2,139
Fed. Royalties $	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	86	82	88	87	90	92	90	86	73	75	83	54	41	19	11	-12
Cumulative	1,071	1,153	1,240	1,328	1,418	1,510	1,600	1,686	1,759	1,834	1,917	1,971	2,012	2,031	2,042	2,029

Explanation of Table Elements

This is the basis of the data used to estimate the quantitative benefit. Data are presented in unadjusted terms.

National Oil Production

The annual and cumulative oil and natural gas liquids production due to the DOE research program. Units are millions of barrels. This is estimated either by direct evidence in completed projects or by modeling assessments. This is net oil production and includes production from exploration reserves and development activities. In other words, this represents the oil and natural gas liquids that are produced in the U.S. due to the DOE oil research program.

National Gas Production

The annual and cumulative natural gas production due to the DOE research program. Units are billions of cubic feet. This is estimated either by direct evidence in completed projects or by modeling assessments. This is net gas production and includes production from exploration reserves and development activities. In other words, this represents the natural gas that is produced in the U.S. due to the DOE oil research program.

Cost Savings $

The annual and cumulative dollar savings from improved efficiencies for exploration, production and refining operations. These dollar savings could be from incrementally more effective use of existing technology (e.g. better seismic technology resulting in fewer dry holes), new technology utilization (less costly drilling), avoided cost (less water production), or general business efficiency (quicker less costly permitting). These savings are estimated either by direct evidence in completed projects or by modeling assessments. These net dollar savings derive from improved efficiencies for exploration, production and refining operations. These cost savings are above and beyond the cost to apply a new technology.

Economic Activity $

The annual and cumulative value in million dollars of the incremental production due to the DOE program. This is directly calculated based on incremental oil, natural gas liquids, and natural gas production in the first two rows times the appropriate product price tracks (historical prior to and inclusive of 1999; AEO forecast for 2000 and beyond).

Public Sector Return $

The Public Sector Return is an estimate of the taxes, royalties and other payments to the pubic entities and the dollars saved. It is calculated from the first three rows of this table. Average tax rates for public sector revenues are based on TORIS studies and include effective rates for Federal Tax, State Tax, and Production and Severance Taxes. These factors are applied to the economic value of the incremental production due to the DOE program. Royalties from Federal Lands are based on historical data from the BLM and the MMS. Taxes and Royalties are added to the dollars saved, resulting in the Public

Sector Return. Annual quantitative values are graphed in constant 1999 dollars at the beginning of this section.

Federal Oil Production

The annual and cumulative amounts of the total U.S. oil and natural gas liquids production on Federal Lands due to the DOE program in millions of barrels. This is a subset of the production in row one.

Federal Gas Production

The annual and cumulative amounts of the total U.S. natural gas production on Federal Lands due to the DOE program in billions of cubic feet. This is a subset of the production in row two.

Federal Royalties $

The annual and cumulative royalty payments from production on Federal Lands. Calculated based on the production in rows one and two times the historical effective royalty rates from the BLM and the MMS.

Background Materials for Economic Realized Benefits

The Total Program Realized Economic Benefit for Seismic Technologies is estimated to be $27.3 Billion.

The Public Sector Return Realized Economic Benefit for Seismic Technologies is estimated to be $8.3 Billion.

The application of seismic technology in oil exploration and development has increased ultimate recovery, and reduced risk and costs by providing a high resolution picture of the reservoir that allows for more effective well placement and reservoir management. Application of seismic technology has increased oil and natural gas production; reduced finding costs; reduced the number of wells needed to drain reserves; reduced the number of dry holes for both exploration & development wells; and increased production from Federal lands and waters, including sub-salt and ultra-deep Gulf of Mexico reservoirs.

Technologies developed in the Department of Energy Advanced Diagnostic and Imaging Program are currently being applied within the U.S. and internationally. Development and application of these technologies ensures a competitive U.S. position in the petroleum exploration and development industry.

The following project descriptions provide examples of the technologies developed and applied in the DOE Advanced Imaging and Diagnostics Program.

Crosswell Seismic Instrumentation, Three-component Seismic Source

Industry/National Lab Partnership, Sandia National Laboratories

The crosswell seismic imaging technology developed in this project minimizes subsurface interference and provides significantly enhanced resolutions of geological features. The technique is capable of "seeing" geological objects at scales of about 5 feet across in comparison to 50 feet across using the traditional technology. The crosswell seismic technology developed is currently being applied.

The tool is designed for use over wide well spacings (~2000'), in deep wells (~15,000'), and at high temperatures (>150° C). The tool's characteristics also include the capability to attach a seismic receiver string below the tool, fiber optic telemetry from tool to surface, 6000 pound peak force, and a present useful bandwidth of ~30-500 Hz (with future extension to ~800 Hz planned). The three-component vibratory source is intended for easy deployment on special heavy-duty wireline and is clamped for good coupling to formation.

Exploration success rates have risen from 17% in 1970 to 48% in 1997 (Energy Information Administration, 1998), in part based on higher resolution seismic methods. By 2010, advanced diagnostics and imaging technology such as this is expected to contribute 100 million bbl per year of additional oil production and over 2 trillion cubic feet per year additional gas production

Crosswell Seismic Instrumentation, Multistation Borehole Seismic Receiver

Industry/National Lab Partnership, Sandia National Laboratories

The multistation borehole receiver developed by this project receives sound waves transmitted between wellbores and/or from surface sources. Whereas the minimum size for a detectable feature using surface seismic technology is about 50 feet, the cross-well imaging technique can detect features as small as 5 feet. By using multiple receiver stations (5 in this case) and by installing a fiber-optic wireline system, the time to conduct the survey was reduced by a factor of 5. Making it 5 times faster than the traditional single-level system. The advanced three-component multistation borehole seismic receivers are designed for 10,000 psi external pressure and >125°C well temperature.

The technology was patented by Sandia National Laboratories in 1992 and manufactured by OYO Geospace in Houston, TX. Bolt Technology, an oil service contractor in Houston, has built three systems: one each for Mobil, Texaco, and Bolt Technology to use in service work. They have conducted between 250 and 300 jobs. Two companies have been formed that have commercialized the product.

Subsalt Seismic Imaging

Industry/National Lab Partnership, Los Alamos National Laboratory

The most widely used technique for exploring offshore areas is seismic imaging. However, conventional seismic imaging techniques fail to locate oil-bearing sediments below or adjacent to the salt structures that cover more than 40 percent of the Gulf of Mexico Continental Shelf. New seismic imaging techniques are needed to efficiently develop the estimated 15 billion barrels of oil and gas equivalent lying under large irregularly shaped salt features in the Gulf of Mexico.

A team of Amoco Production Company, Marathon Oil, Phillips Petroleum, Louisiana Land and Exploration, and Western Atlas International, in partnership with DOE's Los Alamos National Laboratory, are working together to develop advanced seismic processing techniques to increase image resolution at greater depths. The research team has developed three new algorithms to help resolve some of the complex characteristics inherent in 3-D subsalt imaging.

The technology has spurred 16 producers to drill a total of 25 subsalt wildcats in the Gulf. Seven successful discoveries have been reported so far. Industry experts predict at least a 30 percent success rate for subsalt drilling in the Gulf using enhanced seismic processing and modeling techniques. Three of the announced discoveries contain reserves of greater than 100 million barrels of oil equivalent each.

3-D Seismic Data Processing and Modeling, Fourier Method

Industry/National Lab Partnership, Los Alamos National Laboratory

With increased emphasis on finding petroleum in regions of complex structure, there has been a need to develop migration approaches that provide more reliable images of complex regions than can be obtained using the standard Kirchhoff approach, while at the same time maintaining a computational speed comparable to that of Kirchhoff methods. As part of that effort, researchers at Los Alamos have developed a suite of migration methods that are implemented in the wavenumber and space domains and operate on data in the frequency domain.

The two methods that have been developed, whose implementation procedure is similar to that of the well-known split-step Fourier method, are the extended local Born Fourier migration approach and the extended local Rytov Fourier migration approach. Both of these new methods use approximations that are less restrictive than the conventional split-step Fourier approach. Tests using several numerical data sets demonstrate that they give better images than those obtained using the split-step Fourier approach. The Rytov method is superior to the other methods, migrating the dataset about fifteen times faster with an associated decrease in CPU time and increase man-power efficiencies.

4-D Seismic, Lamont Doherty Earth Observatory

4-D or time-lapse seismic technology was developed in a project conducted by Lamont Doherty Earth Observatory and Columbia University. It is a series of repeated seismic surveys used to aid in describing and understanding a reservoir as it changes over time. Time-lapse seismic surveys integrated with other subsurface information help unify reservoir performance data with reservoir and geological models to determine fluid movement in the reservoir.

The technology was patented and commercialized when Columbia University and Western Atlas International, Inc. (now a division of Baker Hughes) entered a joint agreement to market the 4-D software developed in the project. As of May, 1999, the 4-D software is monitoring drainage in almost 50% of all worldwide 4-D field studies. (ref: Western Geophysical webpage: http://www.bakerhughes.com/westerngeo/reservoir/4dseismic.htm)

The technology is being applied to over 60 fields world wide. The best-documented case is the Tiel well drilled for Texaco using 4-D technology. The well came in at 1500-1600 barrels oil per day (bopd), and after several years is still producing at a rate of 600 bopd. Another case is Texaco's Vacuum CO2 project in New Mexico where a 10% increase in oil recovery is expected due to the 4-D effort (Texaco press release, August 1997). Also, Cold Lake Steam Flood in Canada expects a 10%+ increase in recovery of the original oil in place due to 4-D project (Exxon, 4-D Consortium Meeting, July 1996).

The commercialization of this technology created a new area in industry for oil field service companies. Financial benefit from offering this technology to their clients will be in billion's of dollars per year. Western Atlas announced 23 new boats designed specifically for the acquisition of 4-D/4-C data, with the first three launched and active in the North Sea in 1999 (Western Eurotour, April 1997). It is predicted that by 2001, 10-15% of all seismic acquisition will be 4-D. By 2010, 50% of all seismic acquisition will be 4-D (Walter Lynn, PGS Tensor CEO, Offshore Technology Conference talk, May 1997).

3-Component Vibratory Borehole Source

Sandia National Laboratory

The technology developed in this project is a powerful, non-destructive, fieldable vibratory seismic source used as a high-force, wide-bandwidth, three-axis seismic source. Resolution of the tool is about 10 times greater than conventional technology.

The technology is currently commercial and is used for crosswell, reverse vertical seismic profiles, and single-well seismic surveys. This technology may capture a large share of the potential U.S. borehole seismic technology market, which is estimated to be $1.45 billion

4D Seismic in Texaco's Vacuum Field CO2 Project, New Mexico

An expected 10% increase in oil recovery of the OOIP in Texaco's Vacuum CO2 Project in New Mexico is due to the 4-D effort. Texaco hopes to save $8-10 million in well costs; $100 million will be invested in these reservoirs over the next 5 years (4-D Consortium Meeting, January 1997, Texaco press release August 1997)

3D Seismic Interpretation for Reservoir Characterization

Strata Production Company, Brush Canyon Pool, Nash Draw Field, Eddy County, New Mexico

Vertical 3-D seismic profiling and modeling technology developed by Robert Hardage, University of Texas, Austin (working with Strata Production Co.) was used to identify structural anomalies and identify associated horizontal drilling prospects. Surface access was restricted by a playa lake and surface potash mining in the oil lease area. No previous seismic data existed for Nash Draw Field.

A standard seismic modeling package was initially used for modeling Nash Draw. Hardage developed several modifications to this software using instantaneous frequency as a coherency/continuity parameter. The time-to-depth conversion modification allowed for visualization of the Nash Draw zones under the playa and potash mining areas.

The seismic analysis showed that significant reservoir compartmentalization exists at Nash Draw field, and the technology allowed delineation of the compartments. The new methods allowed for identification of productive pay zones and imaging of thin-bed turbidite reservoirs in the Brushy Canyon Unit of the Nash Draw field. Based on identification of reservoir compartments the project now plans drill 6 additional wells under the playa lake and potash mining area to access the 584,000 bbl of additional oil reserves discovered.

In two detailed papers published in 1998 in *Geophysics* (vol 63, no 5) Hardage describes the new technique. Following publication, Dr. Hardage was contacted by the original software company, and asked to incorporate the new methodology into future seismic software package. This is expected to be available in the next 2-5 years.

New Seismic Inversion Model for Reservoir Characterization

Laguna Petroleum, Foster and South Cowden Fields, Texas

Laguna developed a new Seismic Inversion Model based on reprocessing 3-D seismic data to improve vertical resolution of seismic inversion model traces. Reflection time errors, in the form of inaccurate time structure, present in the original data were eliminated.

Seismic inversion modeling is a computer-applied process by which normal seismic traces (wiggle amplitude) are converted to log-like traces. The process converts the conventional seismic response to a quantitative set of data directly related to engineering parameters.

Results of the seismic modeling at Foster and South Cowden fields aided in the identification of the San Andres formation as a "thief zone" stealing production from the Upper Grayburg in this area. Determination not to penetrate the San Andres and produce only from the Upper Grayburg, increased oil production, and decreased water production. The operator realized savings to the project of $30,000 per well.

The 3-D seismic survey identified an additional 570,000 barrels of new reserves in Foster and South Cowden fields. Using the Seismic Inversion Model cost-effective interpretation technique, these reserves were added at a cost of only $0.20 per barrel.

The PI for the Laguna project has been hired to employ the technologies developed in the DOE project including seismic interpretation and recompletion technologies to address similar problems at a field within several miles of the DOE demonstration site. Work at the neighboring field will begin in late August or September 2000.

Seismic Applications in the Williston Basin

Luff Exploration Company, Williston Basin, South Dakota, North Dakota, and Montana

Luff used 2-D and 3-D seismic as an exploration tool in the southern Williston Basin to identify drilling locations in the Red River and Ratcliffe formations. 2-D seismic has been used to locate both Red River and Ratcliffe reservoirs in the Williston Basin, but significant oil has been bypassed. Improved reservoir characterization of the Red River and Ratcliffe for the project was based on reinterpretation of old 2-D seismic surveys and new 3-D seismic surveys.

Two 3-D surveys in Bowman County, North Dakota targeted the Red River formation and revealed the complexity of reservoir porosity. Analysis identified areas of by-passed oil in the Red River. Three new wells were drilled based on these 3-D seismic surveys. Seismic data was particularly useful in identifying small reservoir compartments on the flanks of small Red River structural features. The area of amplitude anomalies identified ranged from 40 to 160 acres each.

A 3-D seismic survey and a special shear-wave seismic survey were obtained in the Ratcliffe area of Richland Co., Montana. The shear-wave survey was a failure, but 3-D seismic data indicated Ratcliffe reserves.

The project did not develop any new seismic technologies, but did for the first time demonstrate the success of 3-D seismic in identifying small compartments on the flanks of Red River structures at depths of 8,500 to 9,500 ft. in the Williston Basin. This information was made public at several workshops in the Williston Basin, and through DOE publications. Several potential drilling areas were identified from the 3-D seismic surveys, and Luff Exploration has continued to follow up on these discoveries with new drilling after the DOE project was completed.

Thin-bed Seismic Attribute Analysis

Diversified Operating Corporation, Sooner Unit, Denver Basin, CO

Diversified used 3-D seismic data analysis techniques to identify reservoir architecture and tailor well spacing and injection patterns to reservoir compartments. A seismic attribute correlation technique that successfully quantified prediction of gross and net pay thickness was developed.

The D sandstone in the Sooner unit is a seismic thin bed at the frequencies recorded and produces a single wavelet at this horizon. Initial seismic modeling indicated that the amplitude of the D sandstone event would be the primary indicator of reservoir-quality sandstone. Ten seismic attributes were picked and analyzed to develop an improved correlation technique. The seismic attribute correlation was used to update the estimates of OOIP made in 1988 and used in the original proposal. The new OOIP estimate is 6.9 million barrels of oil for the D sandstone, approximately 1 million barrels higher than the original estimate. More significantly the seismic attribute correlation method was able to demonstrate a pattern of distribution and to predict where to drill for compartmentalized oil.

The Sooner Unit project was the first 3-D seismic survey in the Denver Basin for exploitation of the D sandstone interval. The 3-D survey imaged the narrow and sinuous reservoir patterns of the fluvial and estuarine environment. The functionality of the seismic images was confirmed by pressure transient tests, which indicated bi-linear flow and channel widths averaging 600 ft. Functional reservoir compartments were found to average 80 acres in size with a major axis of one-half mile and a minor axis of one-quarter mile.

The cost of 3-D seismic for the Diversified project as $250,000 which was equal to the cost (in 1995-6) of completing a single well in the Sooner Unit. Significant cost savings can be realized by use of this seismic attribute technology in predicting drilling locations and avoiding dry holes.

As the result of this field demonstration project, 13 new seismic surveys have been shot in the D sandstone in nearby reservoirs. The 3-D seismic data and technology has been made available through the PTTC regional office in Golden, Co.

Cross-well Seismic for Enhanced Oil Recovery

Chevron, Buena Vista Hills Field and Lost Hills Field, Kern County, CA

Chevron has accomplished several "first's" in their seismic modeling and reservoir characterization of Buena Vista Hills and Lost Hills fields prior to implementing a CO_2 flood. The first high-resolution crosswell reflection images obtained in any oil field in the San Joaquin Valley were obtained using TomoSeis acquisition system at Buena Vista Hills.

As part of this project, Stanford University developed improved velocity imaging algorithms, which will properly handle well deviations and will estimate small amounts of elastic anisotropy. Stanford is also developing improved reflection imaging algorithms, which can handle well deviation, elastic anisotropy and complex structure. Interpretations from the TomoSeis survey have been published and are available to other field operators in the San Joaquin Valley.

The crosswell seismic in was used in conjunction with other data to determine and map the oil saturation in the Buena Vista Hills and it was determined that field was not a good candidate for CO_2 flooding. A similar analysis was applied to reservoir characterization of Lost Hills field prior to its selection for the CO_2 demonstration, which was implemented in June 2000.

Cross-well Seismic and Seismic Attribute Analysis

OXY, West Welch Field, Dawson County, TX

3-D seismic integration improved the history match over the base geologic model results. Evaluation of the seismic responses led to the development of a statistical relationship between pore volume and seismic attributes. Five new wells were drilled based on seismic attribute guided mapping of porosity zones. The crosswell seismic identified a rock type that was not believed to be very extensive in the reservoir based on previous geologic data.

Seismic has also been used in monitoring the movement of the CO_2 flood. Advanced Reservoir Technologies Inc developed a method for using core data at two central wells to calibrate the interwell seismic data to porosity, using the Biot-Gassmann equations. Statistics derived from the interwell data provide an alternative to analog measurements on outcrops. This is the first use of interwell seismic data for this purpose. The first CO_2 monitor survey, which has been recently acquired, suggest a strongly directional flow pattern for the injected CO_2. The crosswell seismic data provided information on the migration and distribution of 60,000 barrels of CO_2 injected since 1997.

Seismic Instrumentation - Geophone Tubing Array, Los Alamos National Laboratory (LANL)

The Fracture Mapping and Slimhole Geophone Array project goal is to make microseismic fracture mapping routine. Downhole micro-seismic mapping and vertical seismic profiling (VSP) surveys in oil and gas reservoirs require costly well preparation and extended instrumentation deployments. Preparation of wells for deployment typically includes removal of tubing and installation of bridge plugs. Other costs include delayed production and returning the well to production. Through-tubing tools will significantly reduce costs of well preparation and return to production.

In 1993, successful through-tubing operations were demonstrated at Prudhoe Bay in Alaska. LANL fielded geophone tools for monitoring microseismicity where the cost of pulling tubing would have been prohibitive. LANL's geophone tools, modified for through-tubing operations in pressurized inclined wells, were deployed through 4-1/2 inch production tubing. An abundance of seismicity, both background and stimulation induced, with an acceptable signal-to noise ratio was observed.

A second use of the geophone was in the massive hydraulic fracturing project conducted by Exxon in the Austin Chalk at Giddings field. Exxon desired a seismic confirmation of drainage volume showing what areas of the reservoir were being contacted by hydraulic fracturing. Fracture location, aerial extent, and vertical containment can be determined by mapping microeathquakes induced during injection. Interpreted results were able to determine the process zone that extended nearly 1 km from the injection well. The reflected arrivals allowed the hypocenter depths to be determined accurately and indicated that the injection was contained within or near the productive interval at the base of the Austin Chalk.

A third use of the geophone seismic mapping technology was in Clinton County, Kentucky to map reservoir fractures. Production-induced microseismicity was monitored at three sites near new, relatively high-volume wells producing from shallow, fractured carbonate reservoirs in south central Kentucky. High quality waveforms were recorded and mapped using only two or three downhole geophone tools.

Background Materials for Economic Options Benefits

The Total Program Options Economic Benefit for Seismic Technologies is estimated to be $20.8 Billion.

The Public Sector Return Options Economic Benefit for Seismic Technologies is estimated to be $7.0 Billion.

Examples of the seismic and imaging technologies that have been developed in the program but have not yet been commercialized are listed below. These technologies, when they become adopted by industry, will provide for: an increase in oil and natural gas production; a reduction in the number of wells needed to drain reserves; a reduction in the number of dry holes, for both exploration & development wells; and an increase in production from Federal lands and waters, including sub-salt and ultra-deep Gulf of Mexico.

Seismic Computational Techniques - Salvo

Industry/National Lab Partnership, Sandia National Labs

Salvo is a code that produces higher quality seismic images than traditional methods. Salvo's algorithmic improvements, designed to use the power of massively parallel computers, result in time savings between 10% and 40%, compared to other programs. Salvo will replace the current primary algorithm, Kirchhoff algorithm, used by the oil industry for 3-D imaging. Researchers have discovered that the Kirchhoff algorithm does not image complex structures to the degree of accuracy currently required; multiple arrivals present a particular difficulty. Salvo was released to project members in October 1996, and preliminary results are promising.

Partners with Sandia National Laboratories include: ARCO Oil and Gas, Conoco Inc., Cray Research Inc., Golden Geophysical Corp., IBM, Intel SSD, Oryx Energy Co., PGS Tensor, Providence Technologies Inc., TGS Calibre Geophysical, and the University of Texas, Dallas.

A typical marine seismic survey dataset can contain over 10 metabytes of data for each shot and over 1 terabyte of data for the whole survey. The time required to read the initial seismic data, read the velocity models, and write the images can be substantial, creating an input/output bottleneck. In Salvo, the input is performed by a subset of available nodes assigned to handle the I/O. The remaining nodes perform the pre-computations in the background, thereby mitigating the I/O bottleneck by performing preliminary computations and data redistributions using nodes not directly involved in the I/O. The trace dataset is distributed across many disks to increase the total disk to memory bandwidth.

To validate Salvo, tests were performed to ensure accurate imaging of reflecting layers. The 3-D SEG/EAGE salt model is an example of a Salvo migration. This synthetic model with synthetic receiver data is available through the SEG home page at http://www.seg.org/research/3Dmodel/SALTHOME/segsalt.html

In 1999, researchers that have developed the algorithms won an R&D 100 Award in the annual competition for innovative technology sponsored by R&D Magazine.

Seismic Modeling Techniques, Advanced Computational Tools Using the SEG/EAGE Model Dataset

Industry/National Lab Partnership Los Alamos National Laboratory and Oak Ridge National Laboratory

The Elastic Modeling Initiative is calculating synthetic elastic data from a portion of the SEG/EAGE salt model, providing substantial new insights into important features of seismic wave propagation through the complex structures that oil and gas will be produced from over the next 5–10 years.

The synthetic seismic data that were computed from the SEG/EAGE salt model contain only "acoustic" wave effects. That means that the data contain only compressional waves. Current exploration often involves areas in which there are large changes in seismic velocities, such as in the Gulf of Mexico area around salt bodies, where compressional wave velocities can be twice those of the surrounding sediments. Such large contrast in seismic velocities can produce efficient conversion between compressional and shear waves. This is referred to as converted or elastic wave propagation.

The Elastic Modeling Initiative was started in response to industry concerns that elastic wave effects are not adequately understood, and that numerical modeling can give greater knowledge of how elastic waves propagate in some exploration situations.

The importance of the Elastic Modeling Initiative is underscored by the increasing acquisition of multicomponent seismic data (such as from ocean-bottom cables). These multicomponent data provide excellent opportunities to record elastic and converted wave data. Another factor increasing the importance of elastic waves is the need for more reliable reservoir models to achieve better recovery of oil and gas from existing reservoirs. Reservoir models must utilize all available seismic, log, and rock physics data. The acoustic response of simple structures is readily modeled, and examples are available for routine use in many practical applications. The elastic response of complex structures is harder to model and similar examples are not readily available.

Seismic Instrumentation, MEMS Accelerometer

Los Alamos National Laboratory (LANL)

The micromachined accelerometer (MEMS) is a member of the class of microelectromechanical systems. As part of the partnership project, Mark Products developed miniature (0.39-inch diameter) vertical and horizontal geophones. LANL designed, fabricated, and successfully tested a wireline-deployed package for the testing and evaluation of miniature accelerometers, geophones, and hydrophones. These sensors were field tested at Amoco, LANL, and Texaco borehole facilities.

Two 2-level, 3-component seismic arrays based on the successful prototype were designed and tested by LANL capitalizing on the MEMS sensors technology. In benchtop testing of the prototype, the MEMS pod qualitatively exhibited sensitivity comparable to a commercial geophone. The redesign reduced the complexity of each pod and streamlined the assembly into an array. Included in the redesign were: improvements in the reliability of the locking arms; specially designed and fabricated feed-through and connectors to accommodate up to 41 electrical conductors; and a flex board circuit to pass power and telemetry through the electronic assemblies of each pod to the pods lower in the array.

The project also demonstrated that the arrays could be deployed and successfully retrieved and evaluated the potential contribution that data from microhole arrays contributed to seismic reflection surveying. A subcontractor to Phillips Petroleum collected 2-D reflection data from conventional surface geophone arrays and two MEMS-borehole arrays. It is believed that this development represents the first reported use of MEMS technology for a borehole seismic array.

LANL has begun preparations with industry for the drilling of a 5000-ft microhole to demonstrate the capability to drill a deep microhole and obtain reservoir information using the microhole instrumentation developed under the Partnership funding.

Background Materials for Economic Knowledge Benefits

1. Knowledge base of basic reservoir properties gleaned from seismic to target exploration and field development potential

University of Texas Austin is working on a new computer algorithm for the efficient and consistent integration of 3-D seismic data, well-log data, geological information, and reservoir production data, into a petrophysical model that can describe and predict the static and dynamic behavior of a hydrocarbon reservoir. The main thrust of the effort is the development of an efficient stochastic inversion algorithm that can exploit the lateral amplitude variations from 3-D pre-stack seismic data and the high vertical resolution available from well-log data. The resultant computer algorithms will be tested, refined, and transferred to the industry.

University of Oklahoma is conducting a project that addresses the prediction and identification of formation damage caused by production operations (reduced reservoir fluids and pressure) or drilling operations (drilling induced shallow water flows). Geophysical seismic surveying technologies are being used to image potential areas within the subsurface where weak rock and soft sediment formation may cause problems or have already caused problems. Seismic imaging technology used in the field is being linked to the mechanical deformational state of the reservoir rocks

2. Knowledge base of seismic acquisition, processing and interpretation

Michigan Technological University is using data from three reservoirs to develop and evaluate methods to calibrate seismic attributes among the various scales of measurement. The expected outcome of the project is a sound physical basis for the use of seismic attributes as tools for reservoir characterization.

3. Tie 3-D/3-C and 4-D seismic more directly to reservoir rock and fluids distributions through attribute analysis to more accurately image the reservoir and high potential regions

Virginia Polytechnic Institute is working to develop advanced seismic methods to determine the statistics of reservoir heterogeneities from seismic data for the purpose of the extrapolating between wells, reservoir characterization, and the simulation fluid flows. Seismic methods will be used to estimate reservoir heterogeneity and cross-validation and will be compared with independent models based stratigraphic and structural elements of geology in outcrops and in reservoirs. Seismic and reservoir models will be integrated to condition petrophysical parameters, e.g., porosity or permeability.

4. Develop algorithms to increase processing efficiency-reduce computational and man-power costs

Background Materials for Environmental Realized Benefits

Advances in 3-D and 4-D seismic technology over the past 25 years have enabled oil and gas producers to evaluate prospects more effectively, drill fewer exploratory wells, and develop fields more efficiently. The result is decreased environmental impact and increased profit.

Seismic technology provides the following environmental benefits:

- More accurate exploratory well siting reduces the number of dry holes and improves overall productivity per well drilled. Development drilling is also improved as fewer dry holes are drilled in delineating the reservoir boundaries and fewer infill wells are drilled to effectively drain reserves. Each dry hole increases the potential to damage surface environments, provide seepage avenues to contaminate aquifers or other zones, and produce wastes (cuttings, fluids, NORM, etc.) that must be disposed of properly.
- Less drilling waste is generated
- Lower produced water volumes through better well placement
- Overall impacts of exploration and production are reduced because fewer wells are required to develop the same amount of reserves

Remote sensing techniques used in conjunction with other exploratory techniques detect and map concentrations of hydrocarbons with greater accuracy than other technologies alone, and with less impact. Remote sensing allows accurate identification of fragile ecosystems enabling care when drilling; improved characterization of earth's natural systems, and identification of spills and leaks in remote areas.

Background Materials for Environmental Option Benefits

The seismic technologies developed in this program can be used to minimize environmental impacts by more accurately determining foundation conditions for offshore facilities prior to placement and reduce water production by better well placement and reservoir management.

Improve target drilling/development activities through the use of seismic technologies will contribute to the minimization of environmental impacts in sensitive environments.

Background Materials for Environmental Knowledge Benefits

The Comprehensive National Energy Strategy calls for maintaining a strong national knowledge base as the foundation for informed energy decisions, new energy systems, and enabling technologies of the future (Goal IV, Objective 1, p.21). The seismic equipment and modeling technology developed in the Department of Energy Advanced Diagnostics and Imaging program can be used to support decision making on future energy options and their effect on the environment by identifying high potential regions with petroleum resources.

Seismic imaging data is currently used by government agencies such as the Minerals Management Service and the United States Geological Survey to identify regions of high petroleum resource potential. This knowledge is used to aid policy decisions about whether to allow exploratory drilling, testing and development of these resources at a minimum overall impact to the environment in sensitive regions such as offshore areas and the North Slope of Alaska.

Background Materials for Security Realized Benefits

Seismic and other imaging technologies developed in this program contribute to security issues by maintaining domestic oil industry infrastructure. The technology allows oil companies to remain profitable by lowering finding costs and development cost. Having existing production and the infrastructure in place allows for increased production in time of crisis.

Advanced seismic technologies also allow the identification of new exploration and development potential within the U.S. Areas with high potential can be tapped to accelerate production in time of crisis. Identification of future reserves to be tapped if and when the U.S. finds a critical need for the energy sources could mitigate the effects of oil price shocks or longer term supply disruptions.

Finally, advanced imaging technologies are being made available to independent operators - both by educating them in the use of the technology and also by reducing the cost of applying the technology. Independent operators are the primary producers of domestic oil and would be relied upon to increase domestic production.

Background Materials for Security Option Benefits

Seismic project results provide a strong national knowledge base that captures the technical expertise of domestic industry to improve efficiency and make it available to all of industry (CNES 1998 Goal IV, Objective 1, page 23)

Background Materials for Security Knowledge Benefits

The R&D and technologies developed will be used within the U.S. and throughout the world to increase both domestic and international oil reserves, further diversifying oil sources and international imports.