Unconventional Gas Recovery Contractors Review Meeting

Agenda, Project Synopses, List of Participants

Held at
Sheraton Lakeview
Morgantown, West Virginia

Sponsored by
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

July 28-29, 1987

TECHNICAL PROGRAM AGENDA

TUESDAY, JULY 28, 1987

7:30 a.m. Registration, Ballroom Foyer
7:30 a.m. Speakers Briefing Breakfast, Reflections Restaurant
8:00 a.m. Morning Coffee and Danish, Ballroom Foyer

Session 1 -- General Session -- Ballrooms A and B

Chairman: Charles A. Komar, Chief, Unconventional Gas Projects Branch, METC

8:30 a.m.	1.1	Welcome -- Hugh D. Guthrie, Extraction Projects Management Division, METC
9:00 a.m.	1.2	Keynote Address -- Stephen S. Ban, Gas Research Institute
9:30 a.m.	1.3	Alternate Fuel Competition -- Robert L. Davies, Energy Regulatory Agency, U.S. Department of Energy
10:00 a.m.		BREAK
10:30 a.m.	1.4	Natural Gas Supply -- Michael German, American Gas Association
11:00 a.m.	1.5	Role of Technology for Unconventional Gas Recovery -- Richard E. Wyman, Canadian Hunter
11:30 a.m.		ADJOURN
11:45 a.m.		LUNCHEON

Session 2A -- Eastern Gas Shales -- Ballroom A

Chairman: Albert B. Yost II, Project Manager, Eastern Gas Shales, METC

1:15 p.m.	2A.1	Project Overview -- Albert B. Yost II, METC
1:30 p.m.	2A.2	Geological Evaluation of Ordovician Shales -- John Roen, U.S. Geological Survey
2:00 p.m.	2A.3	Factors Affecting Devonian Shale Oil Production -- Dwight L. Dauben, Keplinger Technology Consultants, Inc.
2:30 p.m.	2A.4	Development of a Generalized Hydraulic Fracture Model -- Sunder H. Advani, Ohio State University
3:00 p.m.		BREAK

TUESDAY, JULY 28, 1987 (Continued)

3:15 p.m.	2A.5	Database Development for Eastern Tight Gas Formations -- Khashayar Aminian, West Virginia University
3:45 p.m.	2A.6	Multizone Completion Studies -- Gregory Koziar, Columbia Gas Systems Service, Inc.
4:15 p.m.	2A.7	Installation of a Devonian Shale Reservoir Testing Facility and Acquisition of Reservoir Property Measurements -- Charles D. Locke, BDM Corporation
4:45 p.m.	2A.8	Recovery Efficiency Tests -- William K. Overbey, BDM Corporation
5:15 p.m.		ADJOURN

Session 2B -- Deep Source Gas -- Ballroom B

Chairman: William J. Gwilliam, Project Manager, Deep Source Gas, METC

1:15 p.m.	2B.1	Project Overview -- William J. Gwilliam, METC
1:30 p.m.	2B.2	Circum Pacific Sediment Subduction Studies -- Thomas Hilde, Texas A&M
2:00 p.m.	2B.3	Hydrocarbon Generation at the Convergent Margin of Coastal Washington and Oregon -- Parke D. Snavely and Keith A. Kvenvolden, U.S. Geological Survey
2:30 p.m.	2B.4	Thermal History Modeling of Geological Basins -- Michelle A. Kominz, Lamont-Doherty Observatory
3:00 p.m.		BREAK
3:15 p.m.	2B.5	Aleutian Trench Seismic Studies -- Roland von Huene, U.S. Geological Survey
3:45 p.m.	2B.6	Deep Investigative Geophysical Studies -- W. Dal Stanley, U.S. Geological Survey
4:15 p.m.	2B.7	Deep Seismic Reflection Studies in the Pacific Northwest -- Karen L. Cohen, METC
4:45 p.m.	2B.8	Detection/Differentiation System -- Alan Jeffrey, Global Geochemistry
5:15 p.m.		ADJOURN

TUESDAY, JULY 28, 1987 (Continued)

Session 3A -- Poster Session -- Chestnut Ridge Rooms A and B

5:30 - 7:00 p.m — Displays and Reception

3A.1 Unconventional Gas Recovery -- Charles W. Byrer

3A.2 Geosciences -- William F. Lawson
-- Thomas H. Mroz
-- Karen L. Cohen

3A.3 Physical/Chemical Sciences -- Larry C. Headley
-- John France
-- Hsue-Peng Loh
-- Wayne Danen

3A.4 Engineering Sciences -- Leonard E. Graham
-- Kathy Dominic

3A.5 Reservoir Sciences -- J. Keith Westhusing
-- Jim C. Mercer
-- John R. Duda
-- Abbie W. Layne

Session 3B -- Natural Gas Utilization

Chairman: James E. Burchfield, METC

6:30 p.m. 3B.1 Systems Analyses of Advanced Processes -- METC

6:45 p.m. 3B.2 Methane for Use in Chemical Feedstocks -- Gas Research Institute

7:00 p.m. 3B.3 Plasma Chemistry Initiation -- Los Alamos National Laboratories

7:15 p.m. 3B.4 Catalytic Chemistry -- Lawrence Livermore National Laboratories

7:30 p.m. 3B.5 Advanced Catalyst Research for Conversion of Natural Gas to Liquids -- METC

7:45 p.m. 3B.6 Process for Conversion of Methane to Higher Hydrocarbons -- Pittsburgh Energy Technology Center

8:00 p.m. ADJOURN

WEDNESDAY, JULY 29, 1987

7:30 a.m. Registration, Ballroom Foyer
7:30 a.m. Speakers Briefing Breakfast, Reflections Restaurant
8:00 a.m. Morning Coffee and Danish, Ballroom Foyer

Session 4A -- Western Gas Sands -- Ballroom A

Chairman: Karl-Heinz Frohne, Project Manager, Western Gas Sands, METC

8:30 a.m. 4A.1 Project Overview -- Karl-Heinz Frohne, METC

8:45 a.m. 4A.2 Tight Gas Reservoir Characterization -- Benjamin E. Law, U.S. Geological Survey

9:15 a.m. 4A.3 Reservoir Properties Research -- Steven M. Cather, New Mexico Institute for Mining and Technology

9:45 a.m. BREAK

10:00 a.m. 4A.4 Fracturing Materials Research -- Clarence J. Raible, National Institute for Petroleum and Energy Research

10:30 a.m. 4A.5 Two-Phase Flow in Tight Sands -- Prasan Chowdiah, Institute of Gas Technology

11:00 a.m. 4A.6 Fracture Mechanics -- Ronald J. Shaffer and Richard Thorpe, Lawrence Livermore National Laboratory

11:30 a.m. 4A.7 Development of Comprehensive Hydraulic Fracturing Model -- Edmund F. Rybicki and C. Thomas Luiskutty, University of Tulsa

12:00 p.m. LUNCHEON

Session 4B -- Gas Hydrates -- Ballroom B

Chairman: Rodney D. Malone, Project Manager, Gas Hydrates, METC

8:30 a.m. 4B.1 Project Overview -- Rodney D. Malone, METC

8:45 a.m. 4B.2 Geological and Geochemical Factors Affecting the Formation of Gas Hydrates in the Offshore -- George E. Claypool, U.S. Geological Survey

9:05 a.m. 4B.3 Geologic Interrelations Relative to Gas Hydrates Within the North Slope of Alaska -- Arthur H. Lachenbruch and Timothy S. Collett, U.S. Geological Survey

9:45 a.m. BREAK

WEDNESDAY, JULY 29, 1987 (Continued)

10:00 a.m. 4B.4 Evaluation of Geological Relationships to Gas Hydrate Formation and Stability -- Jan Krason and Patrick Finley, Geoexplorers International, Inc.

10:25 a.m. 4B.5 Evaluation of Seismic Data in the Gulf of Mexico -- Richmond Bennett, Columbia Gas Systems Service, Inc.

10:50 a.m. 4B.6 Development of Reservoir Simulation for Thermal Recovery of Heavy Oil/Tar Sands in the Presence of Hydrates -- Sanjay Godbole, University of Alaska

11:15 a.m. 4B.7 Measurement and Modeling of Hydrate Dissociation -- E. Dendy Sloan and Sami Selim, Colorado School of Mines

11:40 a.m. 4B.8 Measurement of Hydrate Thermomechanics -- Richard C. Corlett, University of Washington

12:05 p.m. LUNCHEON

1PM - PREVIEW ROOM MTG ON PUBLICATI & KRASON ON RUSSIA

Session 5A -- Western Gas Sands -- Ballroom A

Chairman: Karl-Heinz Frohne, Project Manager, Western Gas Sands, METC

1:30 p.m. 5A.1 Fracturing Experiments -- Nevada Test Site -- Norman R. Warpinski, Sandia National Laboratories

2:00 p.m. 5A.2 Multiwell Experiment (MWX) Overview -- David A. Northrop, Sandia National Laboratories

2:30 p.m. 5A.3 Multiwell Geology -- John C. Lorenz, Sandia National Laboratories

3:00 p.m. BREAK

3:15 p.m. 5A.4 MWX Fracturing Experiments -- Norman R. Warpinski, Sandia National Laboratories

3:45 p.m. 5A.5 MWX Fracturing Diagnostics -- Paul J. Hommert, Sandia National Laboratories

4:15 p.m. 5A.6 MWX Research Testing -- Paul T. Branangan, CER Corporation

4:45 p.m. ADJOURN

WEDNESDAY, JULY 29, 1987 (Continued)

Session 5B -- Arctic/Offshore Research -- Ballroom B

Chairman: Harold D. Shoemaker, Project Manager, Arctic/Offshore Research, METC

1:30 p.m.	5B.1	Project Overview -- Harold D. Shoemaker, METC
2:00 p.m.	5B.2	Ice Island -- William M. Sackinger, University of Alaska
2:30 p.m.	5B.3	Seafloor Earthquake Measurement System -- Paul J. Hommert, Sandia National Laboratories
3:00 p.m.		BREAK
3:15 p.m.	5B.4	Spray Ice Accretion -- William M. Sackinger, University of Alaska
3:45 p.m.	5B.5	Development and Demonstration of the Arctic Offshore Research Information System (AORIS) -- David L. Chiang, Science Applications International Corporation (SAIC)
4:45 p.m.		ADJOURN

PROJECT SYNOPSES

SESSION 2A

EASTERN GAS SHALES

Chairman: Albert B. Yost, II, METC

OVERVIEW

EASTERN GAS SHALES

by

Albert B. Yost II

Gas from organic-rich shales of the eastern United States has long been a low-volume supply for regional markets but has never been considered as part of the national reserve. The critical issue in further development of the gas shales is in the achievement of linking the wellbore to as much of the natural fracture system as possible. The goal of research in eastern gas shales is to develop the scientific and engineering knowledge base for recovery of natural gas from shale formations that underlie the Appalachian, Illinois, and Michigan basins.

During the first 5 years, research activity was focused on an intensive and comprehensive effort to quantify the geology and geochemistry of the shale formation and to reduce uncertainty surrounding the size of the resource. This lead to a USGS appraisal of 500 to 1,100 Tcf of gas-in-place in 19 plays in the Appalachian basin. Subsequently, research efforts were focused on laboratory and field tests to evaluate stimulation methods for increasing production rates from shale wells. These efforts met with limited success because an understanding of the reservoir was lacking. This lead to a highly instrumented field test (two closely spaced wells offset to a producing well) wherein the productive interval, gas-producing mechanism, and drainage pattern were quantified. This offset well test established that infill drilling of existing producing shale fields appears to be a cost-effective strategy for increasing gas reserves. In established production areas, such as eastern Kentucky, western West Virginia, and southern Ohio, the 3 trillion cubic feet produced to date could be augmented without further exploration.

Currently, research focuses on fundamental reservoir properties in new areas of potential from wells of opportunity, and on the installation of a second offset well test site for understanding reservoir flow behavior. This research entails gathering reservoir property data from 10 sites that have favorable geology and geochemistry in areas of nonestablished production. This information will quantify the magnitude of matrix and fracture porosity and permeability and reservoir anisotropy and will provide the ability to quantify technically recoverable resources for these areas of unknown potential.

Also under study is an effort to increase recovery efficiency using a directionally drilled well in an area of historical production, wherein less than 10 percent of the available gas-in-place is typically produced by stimulated vertical wells. Analysis of shale gas production mechanisms indicates that an increase in the amount of shale surface area connected to the borehole

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may result in more of the adsorbed gas being released and produced over the entire life of the well. Increased recovery efficiency is thought to be achievable by using a directionally deviated well that can be designed to cross natural fractures and can be stimulated to increase the surface area in contact with the borehole. The drilling, coring, logging, and testing of a directionally deviated well is a major field verification effort that measures the key reservoir properties (natural fracture spacing, in situ stress, productive interval, formation permeability, and porosity) that are used in the simulator. These activities also measure the productivity improvement over that of stimulated vertical wells in the area (available baseline data). Results could provide important guidelines for industry in augmenting recovery.

GEOLOGIC EVALUATION OF ORDOVICIAN SHALES

2A.2

Talk to Al about getting samples for Rock-Eval Analysis.

COOPERATIVE AGREEMENT:	#DE A121 83 MC 20422
CONTRACTOR:	U.S. Geological Survey Sunrise Valley Dr. Reston, Va. 22092
CONTRACTOR PROJECT MANAGER:	John B. Roen
PRINCIPAL INVESTIGATORS:	John B. Roen Laure G. Wallace
METC PROJECT MANAGER:	Albert B. Yost II
PERIOD OF PERFORMANCE:	FY 84 - 86

ABSTRACT

The Appalachian Basin contains two widespread sequences of dark shale which contain organic matter. These sequences, the Devonian-Mississippian and the Ordovician black shales, are sufficiently rich in organic matter to be hydrocarbon source rocks. Relative to the younger Devonian-Mississippian sequence, which is shallower and better exposed within the basin, the more deeply buried and mature Ordovician beds have not been extensively evaluated for their hydrocarbon potential. Two regions were selected to make a preliminary appraisal of the Ordovician shales. Each region contains relatively continuous sequences or discrete units of dark-gray to grayish-black shale; however, the structural settings and maturation levels are different. The areas are the unexplored eastern part of the overthrust belt in Tennessee and Virginia, and the drilled northern part of the basin west of the Allegheny front in New York, Pennsylvania, Ohio, and West Virginia.

In the overthrust belt of eastern Tennessee and southwestern Virginia, the prominent black shale unit is the Middle Ordovician Blockhouse Shale. At its type section, in the Blockhouse quadrangle, Blount County, Tennessee, the formation is about 400 feet thick. Other Middle Ordovician units in the overthrust area that contain possible source beds are the Tellico Formation (which directly overlies the Blockhouse), the Sevier Formation, and the Athens Shale (limestone). The aggregate thickness of these formations may be as much as 5,000 feet. Geochemical analyses of weathered samples to evaluate the source rock potential of these formations indicate an average content of about 1% total organic carbon. Maturation levels within the overthrust regime of eastern Tennessee and southwestern

Virginia indicate that if the timing of generation, migration, and entrapment were optimal, then dry gas could be present within the Saltville thrust block.

In the northern part of the Appalachian basin, the black shale sequence is composed of the Upper Ordovician Utica Shale and its correlatives, the Antes Shale, and parts of the Reedsville Shale, Martinsburg Shale and Cincinnatian Series. The thickness of this sequence of black shale ranges from less than 200 feet in the west to more than 600 feet in the east along the Allegheny front. Geochemical analyses show that the sequence contains an average of 1.38% total organic carbon. West of the Allegheny front, the maturation ranges from the diagenetic to the catagenetic stage. The thickest sequence of shale, located in eastern New York and central and eastern Pennsylvania, is in the middle to upper catagenetic stage of maturation and probably produced mostly gas. The thinner sequence of shale, located in the western parts of New York, Pennsylvania, and West Virginia, and the eastern part of Ohio, is in the lower catagenetic stage of maturation and probably produced mostly oil. Assuming the average organic content is 1% and the hydrocarbon fraction of the TOC is 10%, the volume of Ordovician shale studied could have generated approximately 300 billion barrels of oil of which only 1% or 3 billion barrels may have been reservoired.

ACCOMPLISHMENTS

- Analyzed and correlated 147 sample logs prepared from well cuttings.
- Collected 175 Ordovician dark shale samples from 124 localities throughout the Appalachian basin. Evaluated samples using standard pyrolysis methods (Rock-Eval). Samples were also evaluated for total organic carbon (TOC).
- Produced 7 cross section of the dark shale sequence across the basin and isopach, structure, drilling depth, production index and TOC maps.
- Evaluated all data against maturation values defined by the conodont alteration index and the production index (Rock-Eval).
- Defined area of Ordovician age rocks suffiently mature enough to produce oil and gas. Evaluated the genetic potential of the sequence using the following volumetric formula:

  Kilograms of rock x TOC(%) x Hydrocarbon Fraction of TOC(%)

FACTORS AFFECTING DEVONIAN SHALE OIL PRODUCTION

CONTRACT NUMBER: DE-AC21-86MC22140

CONTRACTOR PROJECT MANAGER: Dr. Dwight L. Dauben

PRINCIPAL INVESTIGATORS: Mr. Patrick H. Lowry
Dr. Howard H. Ferrell

METC PROJECT MANAGER: Albert B. Yost II

PERIOD OF PERFORMANCE: May 1986, to July, 1987

ABSTRACT

The objectives of the study are to develop an understanding of the Devonian Shale oil resource and to evaluate procedures which could increase oil recovery. Data were gathered from several sources in West Virginia and Ohio, and entered into a data base management system for further use. The data were analyzed in general over the seven county study area, and more completely in the areas having higher oil production capabilities.

Analysis of the data indicates that the overall resource potential is low. Wells typically produce at high initial rates and then decline rapidly. A key parameter developed from the data is a correlation indicating a relationship of cumulative oil recovery to initial flow potential. Based upon a material balance study, it appears that a significant part of the total in-place oil within the area of influence of a given well is being recovered. An analysis of many wells indicates that completion procedures are important and that damage has probably occurred.

A conceptual reservoir model has been developed to explain the observed production responses. In this model, the producible oil is contained both within the fracture system and a narrow band of matrix surrounding the fracture. The initial producing rate is a function of the fracture width, height, and length. Thereafter, the sustained production comes from the matrix. Computations indicate that the matrix is capable of maintaining relatively high flow rates in spite of its low permeability, as a consequence of the large surface area available for flow and the large imposed pressure gradients on the system. The relatively high oil recovery efficiency appears

to be the result of imposing a large pressure gradient across the low permeability matrix section surrounding the fracture. Analogous laboratory studies are cited in which very high oil recoveries were achieved when imposing a large pressure gradient across a low permeability matrix having an irregular pore structure.

Plans for conducting remedial treatments in the field are now in progress. The goal is to identify wells which have underperformed based upon the initial rates, cumulative recovery, and reservoir pressure. Diagnostic procedures will identify the source of the problem and a treatment tailored for the problem will be applied.

ACCOMPLISHMENTS

Collected data from various sources and created a sizable computer data base.

Produced quadrangle-sized well spot maps for seven county area showing initial producing rates and cumulative production.

Identified areas of highest potential.

Developed a conceptual reservoir model which describes production responses.

Prepared progress report.

Presently performing well studies to identify wells for testing.

DEVELOPMENT OF A GENERALIZED HYDRAULIC FRACTURE MODEL

CONTRACT NUMBER: DE-AC21-83MC20338

CONTRACTOR: The Ohio State University
Department of Engineering Mechanics
Columbus, OH 43210

CONTRACTOR PROJECT MANAGER: Dr. Sunder H. Advani

PRINCIPAL INVESTIGATORS: Dr. Sunder H. Advani
Dr. June K. Lee

METC PROJECT MANAGER: James Mercer

PERIOD OF PERFORMANCE: November 1, 1983 to December 31, 1987

ABSTRACT

Research on a generalized hydraulic fracture model development is aligned with METC's stimulation modeling efforts related to Devonian shales, lenticular sands, methane coal beds, and other target zones. The primary objective of this program is to develop a comprehensive three-dimensional finite element model (FEM) simulator with the effects of layering and differential in situ stress incorporated. Subsidiary goals include the development of a finite element code for predicting in situ stresses in geological strata, establishment of two- and three-dimensional equivalence relations for selected fracture geometries and provision of an interface coupling between the developed hydraulic fracture model and suitable reservoir production simulator.

ACCOMPLISHMENTS

- The developed three-dimensional hydraulic fracture model utilizes the discretized FEM fluid flow momentum equations in the plane of the crack, the mass conservation equation, the crack pressure-width relation for layered media, and an energy release rate mediated fracture propagation criterion. Several numerical simulations for fracture geometry representation have been conducted. Selected comparisons with corresponding responses from other reported models have also been performed.

- The In Situ Stress Analysis Program (ISAP) provides a capability for simulating principal stresses and potential fracture zones in formations with specified material properties, layering interface, and stress/displacement boundary conditions. This code has been used to evaluate stress trajectory and stress ratios for various field examples.

- Governing equations for the benchmark cases of penny-shaped and elliptic fracture models in a uniformly confined, linear elastic, homogeneous medium have been derived using a variational formulation. Closed form explicit solutions for the generalized co-ordinates representing the major fracture dimensions have been obtained. Comparisons with PKN and CGDD models and other models provide a rational basis for establishing response equivalence. In addition, the three-dimensional FEM codes have also been validated against these solutions. Solutions for non-Newtonian fluid flow in a reservoir, for leak-off characterization, have also been obtained.

- Investigations on interface coupling of the FEM hydraulic fracture simulator with a reservoir production model have been initiated. This coupling is being accomplished at each fracture surface node by characterizing effective fracture permeabilities.

PUBLICATIONS

Advani, S.H., Khattab, H., and Lee, J.K. May 1985. Hydraulic Fracture Geometry Modeling, Prediction, and Comparisons. Proceedings 1985 SPE/DOE Symposium on Low Permeability Reservoirs, SPE/DOE Paper No. 13863, 135-164.

Advani, S.H., Torok, J.S., and Lee, J.K. 1985. General Solutions for Piston-Like Displacement of Compressible Fluids in Porous Media. Journal of Energy Resources Technology, Trans. ASME, 107, 523.

Advani, S.H., Torok, J.S., and Lee, J.K. 1986. Explicit Approximate Solutions Associated with the Mechanics of Hydraulic Fracturing. Journal of Applied Mechanics, Trans. ASME, Vol. 53, 462.

Advani, S.H., Lee, J.K., Khattab, H., and Gurdogan, O. June 1986. Fluid Flow and Structural Response Modeling Associated with the Mechanics of Hydraulic Fracturing. SPE Formation Evaluation, SPE Transactions, 309-318.

Advani, S.H., Torok, J.S., Lee, J.K., and Choudhry, S. Explicit Time-Dependent Solutions and Numerical Evluations for Penny-Shaped Hydraulic Fracture Models. In press, Journal of Geophysical Research.

Advani, S.H., Lee, J.K., Lee, T-S, Jinn, J-T, and Choudhry, S. 1987. Fracture Mechanics Modeling Associated with Layered Rock and Bi-Material Interfaces. In press, Proc. 28th U.S. Symposium on Rock Mechanics.

Torok, J.S. and Advani, S.H. 1987. Non-Newtonian Fluid Flow in a Reservoir - An Application to Hydraulic Fracturing. Journal of Energy Resources Technology, Trans. ASME, 109, 6.

DATA BASE DEVELOPMENT FOR EASTERN TIGHT GAS FORMATIONS

CONTRACT NUMBER: DE-AC21-85MC22189

CONTRACTOR: West Virginia University
Department of Petroleum and Natural Gas Engineering
College of Mineral and Energy Resources
Morgantown, West Virginia 26506
304/293-5695

CONTRACTOR PROJECT MANAGER: Professor S. Ameri

PRINCIPAL INVESTIGATORS: Professor S. Ameri
Dr. K. Aminian

METC PROJECT MANAGER: Albert B. Yost II

PERIOD OF PERFORMANCE: November 1, 1985 to June 30, 1987

ABSTRACT

The Appalachian Basin contains a number of low permeability formations which have produced natural gas for many years. The lack of reliable data/information pertaining to parameters controlling production of natural gas from such low permeability (tight) gas bearing formations has hindered their economical development. The data that have been available usually consisted of isolated data points held within a company's files without a mechanism for comparison with similar formation(s) in the Appalachian Basin. This has effectively prohibited the development of any kind of statistical base from which one might infer the production mechanism, predict performance, determine the responsiveness of formations to stimulation treatments, and delineate the high potential areas for future development.

The overall goal of this study was directed towards answering some of the key questions that could make the eastern low permeability formations viable candidates for future development. This research project endeavored to solve the problem, at least for a subset of tight gas bearing formations, consisting of Big Injun, Berea, Benson, Oriskany, etc., that exist in the Appalachian Basin.

The research objectives have been achieved through: (1) development of a Data Base through collection, interpretation, and compilation of data relative to completion, production, and stimulation on the eastern tight gas formations so that a good research foundation could be established and (2) analysis of the data so that the key parameters affecting gas production could be

identified and quantified. It should be noted that the Data Base contains data on over 1000 wells in Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia. The information was collected from a variety of sources including many gas companies.

The Data Base can be utilized to identify and evaluate a range of lithological, reservoir, and treatment parameters which control the production of natural gas from the eastern tight gas formations. The utilization of the data base and its applications relative to identification and evaluation of potential areas for future economical development are discussed in this paper.

ACCOMPLISHMENTS

- Data relative to completion, production, and stimulation on over 1000 wells in Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia have been collected.
- A Data Base has been developed through collection, interpretation, and compilation of data on the eastern tight gas formations.
- Identification of high potential areas for future economical development through multiple completion/recompletion.
- Evaluation of production characteristics and development of production decline curves.
- Evaluation of responsiveness of the formations to stimulation.

ARTICLES AND PRESENTATIONS

"Data Base for Eastern Gas Bearing Formations: Development and Applications", Proceedings of SPE Eastern Regional Conference, 1987 (to be published).

"Economic Evaluation of Multiple Completion", ISA, Proceedings of Pittsburgh Modeling and Simulation Conference, April 1987.

"Developing Gas Resources in Appalachian Basin Through Recompletion: An Economic Feasibility Study", SPE 15923, Proceedings of SPE Eastern Regional Conference, November 1986.

"Production Decline Type Curves for Gas Wells Producing Under Pseudo Steady-State", SPE 15933, Proceedings of SPE Eastern Regional Conference, November 1986.

"A Systematic Approach for Economic Development of the Devonian Shale Gas Resources", SPE 14504, Proceedings of SPE Eastern Regional Conference, November 1985.

MULTIZONE COMPLETION OPPORTUNITIES IN THE APPALACHIAN BASIN

CONTRACT NUMBER: DE-AC21-86MC23140

CONTRACTOR: Columbia Gas System Service Corporation - Research Department
1600 Dublin Road, PO Box 2318
Columbus, OH 43216-2318
(614) 481-1495

CONTRACTOR PROJECT MANAGER: Gregory Koziar

PRINCIPAL INVESTIGATORS: Gregory Koziar
James L. Wallace

METC PROJECT MANAGER: Charles W. Bryer

PERIOD OF PERFORMANCE: July 19, 1986, to August 31, 1987

ABSTRACT

The primary goal of this project is to increase exploitation and development of Devonian shale gas reserves outside historically productive shale regions within the Appalachian basin. This goal will be accomplished by demonstrating to producers, the economic viability of Devonian shale gas potential in those nonhistoric areas. The objectives of this project are to:

- Create an atlas identifying areas of Devonian shale gas potential,
- Partition and rank each area on the basis of expected reservoir quality and production potential, and
- Demonstrate the economic benefits of including the shale as a secondary completion target.

The present economic climate is unfavorable for nonhistoric shale gas development. In light of this, the approach taken is to exploit the Devonian shale as a secondary completion interval in geographic areas where producers are actively drilling to some other horizon. The shale could then be developed through dual or commingled completion in new wells or by recompletion or deepening in existing wells.

This project consists of two phases: Phase 1 - the study of shale potential in the Jackson - Kanawha counties, West Virginia, is nearing completion; Phase 2 will continue the study but to a larger area of the basin.

Work performed thus far includes: screening of drilling and completion records from state surveys in Kentucky, Ohio, West Virginia, and Virginia for identification of areas under active development; obtaining available maps, cross-sections, and geologic/reservoir reports; and, collecting logs, reservoir property and production information. From these data, various maps have been constructed, production decline curves generated, and economic

analysis performed. Production history matching is being conducted to determine kh values which will be used to create a reservoir quality partitioning map.

Virtually all shale wells in Phase 1 area are average and below-average producers. Under the prevailing economic conditions, nonhistoric shale gas well drilling is attractive for only the above-aveage case. However, Devonian shale gas development is very attractive in most other cases as a secondary completion zone in dual and commingled completions or in recompletions and well deepenings.

The future work to be performed consists of completing Phase 1 map generation and partitioning the study area. Phase 2 will consist of extending the Phase 1 work to peripheral areas and incorporating risk into the analysis.

The major benefit of this program from a producer's standpoint will be the maximization of gas well success ratio. This project is important to the fossil fuel program in that it could significantly contribute to the development of nonhistoric shale gas reserves with virtually no field demonstration costs.

ACCOMPLISHMENTS

- Identified areas of drilling and completion activity within the basin.
- Identified the productive horizons in the study area and established decline curves for the major producing zones.
- Constructed structure and isopach maps on several producing formations.
- Constructed cross-sections throughout the study area.
- Performed economic analyses on 24 cases involving single zone, dual, and commingled completion as well as recompletion and deepening to the shale.
- Determined that for most situations studies, the Devonian shale in the Phase 1 study area is economically attractive as a secondary completion interval.
- Performed production data history matches to determine the permeability-thickness product for use in partitioning the area.

PRESENTATIONS

Koziar, G. 1987 February 24-25. Multizone Completion Opportunities in the Appalachian Basin. Peer Review Of Unconventional Gas Recovery-Eastern Gas Shales. Rockville, Maryland

INSTALLATION OF A DEVONIAN SHALE RESERVOIR TESTING FACILITY AND ACQUISITION OF RESERVOIR PROPERTY MEASUREMENTS

CONTRACT NUMBER: DE-AC21-84MC21216

CONTRACTOR: The BDM Corporation
7915 Jones Branch Drive
McLean, VA 22102

CONTRACTOR PROJECT MANAGER: C. David Locke

PRINCIPAL INVESTIGATORS: Dr. James N. Kirr
J. Graham McCleary
Michael A. Grabowski

METC PROJECT MANAGER: Albert B. Yost II

PERIOD OF PERFORMANCE: September 30, 1984 to October 31, 1987

ABSTRACT

The primary purpose of this project is to obtain reservoir flow and property measurements in designated target areas of Devonian shale occurrence where only minimal information on reservoir potential is known, to identify a suitable site for an offset well reservoir testing facility, and to install and operate the testing facility to obtain detailed reservoir information. The project is designed to expand the knowledge base for understanding and predicting of reservoir performance in these newer areas of potential Devonian shale production. A two-phase research and development project has been initiated to acquire the necessary data. Phase I involves measurement and analysis of reservoir properties in target areas of Michigan, Illinois, New York, Ohio, Pennsylvania, and West Virginia. Reservoir data include such properties as fracture and matrix porosity and permeability; natural fracture frequency, reservoir pressure and flow performance, and shale mechanical properties. These data were developed in conjunction with oil and gas operators through wells of opportunity. Phase II involves the installation of an offset well facility by drilling wells offset to an existing base well, followed by design and execution of offset well testing. Offset well testing will include well-to-well and multi-well interference tests, build-up, and drawdown tests to determine reservoir properties. Fracture diagnostic experiments will also be conducted.

The most radioactive zones within the target shale were cored in the wells-of-opportunity using a 60-foot oriented core barrel with a PVC inner barrel liner and a 7-7/8" x 3-1/2" Stratapax core bit. Low rpm's and reduced weight-on-bit (6,000 - 10,000#) were used for the coring procedure to insure maximum recovery. The cores were cleaned, described, and sampled in the field for desorption testing. Those samples were desorbed for up to 240 days to determine their gas content. Remaining core was removed from the field

for complete fractographic analysis and detailed description. Samples were then sent to laboratories for petrophysical analysis and mechanical properties testing. Core-derived data include water saturation, gas permeability, porosity, vitrinite reflectance, rock fabric description, lithologic description, directional ultrasonic velocity, point load induced fracturing, and directional tensile strength.

The wells-of-opportunity were tested in their "natural" condition if posssible; however, with one exception, all wells required some form of stimulation before obtaining a measurable gas flow. Log-log, semi-log, and square-root-of-time plots were made of the data as appropriate to determine flow regimes and to calculate reservoir parameters. Computer simulation of the tests were then used to verify or refine the values calculated from the conventional analyses.

ACCOMPLISHMENTS

- Seven wells-of-opportunity have been cored and logged; thirteen wells have been tested.
- One well-of-opportunity has been determined suitable for establishment of the offset well test facility at its location in Whitley County, Kentucky.
- Rhinestreet Shale targets in the Appalachian Basin were found to have slightly higher porosity than the primary gas-producing shale horizon (Huron) and comparable gas content. However, the areas tested appeared to be less-fractured and/or have less conductive fracture systems.
- Commercial or near-commercial production was found in the Antrim Shale in Michigan and in the Chattanooga Shale in Kentucky.
- Marcellus targets in central West Virginia and northern Pennsylvania were found to have gas production potential, but was also water productive.

ARTICLES AND PRESENTATIONS

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Kirr, James N. 1987. Devonian Shale Production in Whitley County, Kentucky. 18th Annual Appalachian Petroleum Geology Symposium, Morgantown, WV. Abstract, p 33.

RECOVERY EFFICIENCY TEST

CONTRACT NUMBER: DE-AC21-85MC22002

CONTRACTOR: The BDM Corporation
7915 Jones Branch Drive
McLean, VA 22102

CONTRACTOR PROJECT MANAGER: William K. Overbey, Jr.

PRINCIPAL INVESTIGATORS: William K. Overbey, Jr.
Richard S. Carden
C. David Locke

METC PROJECT MANAGER: Albert B. Yost II

PERIOD OF PERFORMANCE: September 30, 1985 to June 15, 1988

ABSTRACT

The objective of this project is to determine the recovery efficiency of a directionally drilled horizontal wellbore oriented to take advantage of the natural permeability anisotropy of Devonian-age gas-bearing shales. A further objective is to compare the increased recovery efficiency resulting from inducing multiple hydraulic fractures along the length of the horizontal wellbore. The project is designed to investigate geologic parameters which will affect performance of a producing gas well and control the orientation of induced hydraulic fractures. The project also examines spacing between natural fractures and the configuration of fractures induced during stimulation. To accomplish the stated objectives, the following tasks had to be performed: (1) select a drill site; (2) evaluate the reservoir; (3) formulate a drill plan; (4) drill the well; (5) test and analyze the well; and (6) hydraulically fracture and test the well.

BDM selected the site; worked with METC modelers to evaluate the reservoir; planned the drilling operation; drilled the well; and tested the natural production capacity of the well. Initial open flow rates (120 mcfpd) were very close to those predicted by the reservoir model, but the rates declined rapidly to a stablized rate of 34 mcfpd against 40 psi line pressure. This is believed to be due to a lower than anticipated reservoir pressure of 140 psig versus an expected pressure of 260 psig. Installation and initial testing of the horizontal wellbore will have a major impact on the direction of future FE R&D activities on unconventional gas reservoirs.

ACCOMPLISHMENTS

- o Selected the best Devonian Shale normalized producing area.
- o Simulated reservoir production history with METC and recommended three specific sites to DOE/METC.
- o Developed a site specific well prognosis and successfully drilled the world's first horizontal well drilled with air as circulating fluid.
- o Logged, cored and produced the first video camera survey of an air-drilled horizontal well.
- o Deployed eight external casing packers to separate the well into seven zones which were tested individually through integral ported collars.

ARTICLES AND PRESENTATIONS

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NOTES

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SESSION 2B

DEEP SOURCE GAS

Chairman: William J. Gwilliam, METC

DEEP GAS

by

W. J. Gwilliam[1]

ABSTRACT

Deep source gas research represents one aspect of a broader Government program investigating unconventional natural gas resources (UGR). There is general agreement that natural gas will continue to be an important alternative to other energy sources. In general, UGR research has been focused on low porosity, low permeability, or otherwise undeveloped resources whose source rocks and/or reservoirs are at conventional depths ($\leq$ 15,000 feet). In addition to these resources, speculation on the existence of deeper gas source rocks and/or reservoirs has persisted since the early 1900's with the advent of the abiogenic theory of mantle origin petroleum. A brief description of this and other concepts for deep hydrocarbon emplacement include:

- Abiogenic Gas -- Gas of nonbiologic origin emplaced primordially or generated chemically in the Earth's mantle.
- Subducted Organic-Origin Gas -- Gas generated as a result of deep plate tectonic emplacement of hydrocarbon-generating source rocks in the Earth's crust.
- Deep Sedimentary Basin Gas -- Gas generated from and reservoired in deeply subsided sedimentary rocks.

Until recently, the Department of Energy has concentrated its research efforts exclusively on the subducted organic-origin gas hypothesis. Central to all of this research is the idea that natural gas can be generated in sediments carried to great depths in the Earth's interior and potentially source gas to shallower drillable traps through deep fracture systems. Very early in the project, the Cordilleran Geologic Province of western North America surfaced as a conspicuous candidate for study because of its modern (active) and fossil (inactive) subduction zones. Although many areas of North America appear to have experience convergent plate tectonic activity in past geologic times, the western Cordillera contains thrust fault structures that enabled deep emplacement of hydrocarbon-generating sediments during more recent geologic ages (during the last 180 million years). For this reason, the Cordilleran Geologic Province has been designated as the prime study area for the project. The specific area of interest in this province encompasses approximately

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1.5 million square miles of the western United States (including Alaska) and Canada; other portions of this same province extend southward into Mexico and Central and South America.

To date, project results are encouraging in terms of locating thick subduction zone sedimentary rock units, with geophysical studies, that were predicted to occur in the deep subsurface of western Washington state and in south central Alaska. Preliminary geochemical studies indicate that the deep gas generating capacity of the Aleutian Trench of southern Alaska is high (up to 212 trillion cubic feet [Tcf]) during the last 20 million years alone.

As part of a recent management restructuring of unconventional gas resource research, increased attention has been directed toward deep sedimentary basin gas while maintaining fundamental research associated with subduction. While current industry activity is at an all-time low, there is an established trend nationally and internationally toward deeper penetration of established petroleum producing basins. Accordingly, the Department of Energy will examine research problems surrounding deep hydrocarbon exploration and production (i.e., deep reservoirs).

SUBDUCTION ZONE TECTONIC STUDIES TO DEVELOP CONCEPTS FOR THE OCCURRENCE OF SEDIMENT SUBDUCTION, Phase II

CONTRACT NUMBER:	DE-AC21-83MC20213 Project RF-49060000
CONTRACTOR:	Texas A&M Research Foundation Box 3578 College Station, Texas 77843
CONTRACTOR PROJECT MANAGER:	Ms. Charlene Miller
PRINCIPAL INVESTIGATORS:	Dr. Thomas W.C. Hilde
METC PROJECT MANAGER:	Mr. William J. Gwilliam
PERIOD OF PERFORMANCE:	June 1, 1983 to September 30, 1986

ABSTRACT

The primary purpose of this project is to define the tectonics of sediment subduction in the world's deep ocean trenches. The program employs existing bathymetric data supported by marine seismic reflection, gravity, magnetic and side-scan sonar data. This information has been compiled in an effort to define structures of trenches, sediment distribution and deformation through various stages of plate convergence, and the sediment subduction/accretion balance based on the factors controlling the fate of sediments at the trench. The overall sediment budget and the evolution of trench sediments (determined by sediment volumes, rates of accumulation and tectonic framework) are important factors in predicting the ultimate fate of organic-rich sediments and the potential for exotic gas accumulations in the trench-slope.

Numerous bathymetric profiles in all the world's trenches have been compiled and stacked in order to facilitate correlation of structures. Tectonic features maps have been produced illustrating the major tectonic elements such as plate bending-induced faults, fracture zones, fold structures, seamounts, exposed basement, extent of turbidite infill, slumps and the locations of the trench outer rise, trench slope break and trench deformation front. A circum-Pacific analysis of accreted sediment is being made based on our trench gravity modeling which indicates that a trench axis/free-air gravity minima relationship exists that may reflect volume of accreted deposits. We have recently moved toward fully interactive handling of our data sets

with the aid of a three-dimensional graphics system and the associated software developed for this purpose. Data can now be quickly displayed and manipulated in three dimensions. This facilitates the correlation of features and greatly aids the overall interpretative process.

Through combining plate roughness maps with seismic reflection data, estimates can be made of the balance between fault-induced void space and sediment volumes accommodated during tectonic displacement of sediments. Our findings indicate that much of the sediment arriving at the western Pacific trenches can be accommodated in subduction. One notable exception is the Nankai Trough where sediment volumes far exceed plate relief and accretion results. The detailed behavior of the decollement is an additional parameter which affects the process of subduction and accretion. Recent studies (Morris et al, 1987) relating ^{10}Be concentrations in some volcanic arcs with incorporation of subducted sediments during magma mixing provide compelling evidence for widespread subduction of at least Pliocene and older sediment. Presently, the earth is girdled with 37,000 km of subduction zones, where plates are subducting at an average rate of 80 km/Ma (Reymer & Schubert, 1987). Morris et al (1987) estimate that approximately 2×10^5 km^3 of sediment may be subducted per million years based on sediment incorporation into grabens averaging 0.3 km deep, 1 km wide and covering 20% of the subducted seafloor.

ACCOMPLISHMENTS

* Stacked over 2,000 bathymetric profiles by trench regions worldwide. Profiles aligned on trench axis. Navigational plots for all trench regions accompany the profiles.

* Constructed over 80 tectonic features maps for all trench regions covering 2^o seaward of the trench and 1^o arcward of the trench.

* Completed detailed regional studies in areas of high data density including the Mariana, Peru, S.W. Japan, Panama and Tonga Trenches.

* Interpreted individual seismic reflection lines for graben and sediment volumes and nature of interaction between plates, faults and sediment in the area of the decollement.

* In process of preparing a map of trench slope accreted sediment distribution based on the inflection point in the free-air gravity signature over the trench.

* Preparing sediment budget studies based on subducting plate roughness versus amount of sediment in trenches.

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ARTICLES AND PRESENTATIONS

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Ku, K. 1985. Sediment Accretion and Subduction Processes in the Nankai Trough. M.S. Thesis, pp. 139. Department of Geophysics, Texas A&M University.

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Rader, B.L. 1985. Sediment Trench Fill Effect on Trench Age-Depth Relation. M.S. Thesis, pp. 107. Department of Geophysics, Texas A&M University.

Wright, D. 1986. Proposed Nature of the Westward Bend in the Tonga Trench, Southwest Pacific. M.S. Thesis, pp. 120. Department of Oceanography, Texas A&M University.

Warsi, W.E.K. and Hilde, T.W.C. 1987. Incipient Spreading Within the Nazca Plate: A Consequence of Subduction Along the Peru Trench. Proceedings, Pacific Rim Conference '87, Gold Coast, Australia.

HYDROCARBON GENERATION AT THE CONVERGENT MARGIN OF COASTAL WASHINGTON AND OREGON

CONTRACT NUMBER: DE-AI21-83-MC20422

CONTRACTOR: U.S. Geological Survey
Branch of Pacific Marine Geology, MS-999
345 Middlefield Road
Menlo Park, CA 94025

CONTRACTOR PROJECT MANAGER: John B. Roen

PRINCIPAL INVESTIGATORS: Keith A. Kvenvolden
Parke D. Snavely, Jr.

METC PROJECT MANAGER: William J. Gwilliam

PERIOD OF PERFORMANCE: January 1, 1984 to September 30, 1987

ABSTRACT

This activity, initiated in FY-84, involves the investigation of the hydrocarbon generation potential of the ancient counterparts of a modern subduction complex. The objective is to test a geologic model of the convergent margin of Washington and Oregon so that broad exploration targets and the petroleum potential of subducted Tertiary sedimentary rocks can be evaluated. This model involves periods of more head-on convergence between Pacific and North American plates during mid-late Eocene and late middle Miocene times, which produced thick accretionary wedges of melange and broken formation which are exposed onland only along the west side of the Olympic Peninsula. Siltstones containing organic matter have taken part in the accretionary process and have experienced thermal regimes conducive to the generation of large quantities of gas and lesser amounts of oil. Numerous oil and gas shows in exploration wells drilled along the west side of the Olympic Peninsula attest to the potential of melange as source rocks. During FY 84 through 86 about 160 samples, chiefly from biostratigraphically dated strata, were collected from widely spaced localities and analyzed for vitrinite reflectance and source rock characteristics. These analyses indicate that most of the sedimentary rocks in the middle to late Eocene Ozette melange and in the late Oligocene to middle Miocene Hoh melange and broken formations are marginally mature and have low contents of Type III organic matter which is more gas than oil prone. Gas samples were collected from active seeps and an abandoned test well for hydrocarbon and isotopic analysis. Geochemical analyses were also completed on samples of crude oil from the Sunshine Medina No. 1 well and from the Jefferson oil seep. Comparisons were made between molecular markers in the oils and in extracts from melange. The geochemical data are being incorporated into the geologic framework leading to a final report at the end of FY 87. Interpretation of 24-channel seismic reflection profiles, together with geological and geochemical studies on the Oregon continental margin in FY 87, will provide a framework for a cross section that

extends from the upper continental slope eastward to the Mist gas field in northwest Oregon.

ACCOMPLISHMENTS

- The middle Eocene Ozette melanges and broken formation appears to be the source of oil and gas in the coastal Olympic Peninsula of Washington although the source rock quality is marginal.

- Rock Eval analyses indicate that Ozette melange and late Oligocene to middle Miocene Hoh melange contain predominantly Type III kerogen which is more prone to the generation of gas than oil.

- Organic matter in these melanges is generally mature with respect to oil generation but marginally mature with respect to gas generation.

- With one exception, the gases from seeps and one test well have similar carbon isotopic compositions of methane but variable molecular compositions of hydrocarbon components.

- High vitrinite reflectance values (Ro) generally occur along major faults probably due to frictional heating of the rocks.

- Oil has migrated along thrust(?) faults into rocks as young as middle Miocene.

- Oil, reservoired in the middle Miocene Hoh melange at Medina No. 1 well, oil from Jefferson seep, and oil in microseeps in middle Eocene melange "smell muds" in coastal outcrops are all genetically related.

- Petroleum found along a 140 km stretch of coastal Washington north of Grays Harbor apparently is composed of a single oil-type, and possibly gas-type, that was generated from a common source, namely the middle Eocene Ozette melange.

- Potential targets for gas exploration may exist where Eocene strata underplate lower and middle Eocene basalts and sediments as along the Crescent thrust.

ARTICLES AND PRESENTATIONS

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THERMAL HISTORY MODELING OF GEOLOGICAL BASINS

Contract Number: DE-AC21-85MC22009

Contractor: Columbia University
Lamont-Doherty Geological Observatory
Palisades, NY 10964

Contractor Program Manager: Charles Komar

Principal Investigators: Gerard C. Bond
Michelle A. Kominz
Daniel M. Davis

METC Project Manager: William J. Gwilliam

Contract Period of Performance: October 1, 1985 to January 14, 1989

ABSTRACT

The purpose of this study is to develop a generalized thermal model for forearc prisms, and to apply the model specifically to the Oregon-Washington and southern Alaska margins. The predicted thermal history of the sediments will then be used to predict the likelyhood of the production of significant accumulations of gas in these regions.

We plan to produce two levels of thermal model and 3 levels of results. First, we will produce a simple descending slab model which will focus on the large scale tectonic and thermal features operating in the forearc region. It should provide insight into which of these features are likely to be important, and thus must be included in the thermal modeling of the forearc prism. It should also provide much of the initial and boundary conditions needed in setting up the more detailed, second level modeling of the forearc prism.

The second level of model, the forearc prism model, will focus on the processes operating within the forearc prism. The subduction processes operating in forearc prisms are complex, and many simplifying assumptions must be made in order to apply a geophysical model to the problem. We plan to use the Coulomb failure criterion in order to characterize the overall sediment motion, the general stress field, and the overall porosity distribution within the deforming wedge. Heat flow within the prism will be assumed to result from conduction, advection, radioactive decay and frictional shear heating within the sediments. Additional mass sediment motion which we hope to model includes the draping of sediments on the top of the wedge and the underplating or off-scraping of sediments at the base of the wedge.

This model will first be applied to a wide range of possible scenarios in order to determine the sensitivity of the model results to different model assumptions. In order to constrain the bounds on variability in input assumptions and in order to try to encompass much of the variety observed in modern forearc prisms, a great many observations must be compiled. For this purpose we are developing a relational, graphically oriented data base that will contain information published on forearc prisms around the world.

Finally, the model will be applied to observed forearc prism wedges in Oregon-Washington and in Alaska. Results from the generalized modeling should point to the data which are the most critical in obtaining accurate estimates of the thermal history of these margins. We will compile a detailed data base for these specific margins. These data will be used both as input for the model and modeling assumptions and also for comparison with the results predicted by the model.

Results from the descending slab model indicate that the temperature structure of the subducting slab and the rate of subduction have a significant effect on the temperature structure near the prism, while frictional heating has little effect. The large scale temperature structure near the forearc does not change greatly with time in the Oregon-Washington or Alaska margins, however, because the age of the descending plate as it enters the trench has remained nearly the same for the last 20 m.y.

ACCOMPLISHMENTS

- Developed a thermal model of descending oceanic slab including:
  - Conductive heating
  - Frictional heating
  - Variable initial temperatures of overriding and descending slab
  - Variable rates of subduction
- Test the sensitivity of the descending slab model to various conditions, including:
  - Time step used in calculation
  - Age of descending plate
  - Rate of subduction
- Apply the descending slab model to known convergence rates in the Oregon/Washington and Alaskan margins
- Establish data base for forearc prisms
- Begin thermal model of forearc prism sediments

DEEP SOURCE GAS PROJECT, SUBTASK A 2B.5

CONTRACT NUMBER: DE-AI21-83-MC20422

CONTRACTOR: U.S. Geological Survey
Branch of Pacific Marine Geology
345 Middlefield Road
Menlo Park, CA 94025

CONTRACTOR PROJECT MANAGER: John B. Roen

PRINCIPAL INVESTIGATORS: Roland von Huene

METC PROJECT MANAGER: William J. Gwilliam

PERIOD OF PERFORMANCE: October, 1985 to September 30, 1987

ABSTRACT

This study is a quantitative test of the idea that convergent margins can contain significant accumulations of hydrocarbon gas derived from subducted sediment. We studied the eastern Aleutian Trench where thick deep-sea-fans containing organic matter are subducted. The study was designed using the concept that organic matter in subducting sediment passes through elevated temperatures where gas is generated. The gas escapes upward and is trapped in the overlying plate. If the volume of sediment and its organic carbon content are known, the potential volume of gas generated can be calculated.

DSDP drilling and extensive USGS geophysical and geological studies provide our basic information. We first did a preliminary two-dimensional study to see how well gas generation could be quantified and whether the potential volumes of gas were sufficiently large to constitute a resource (Kvenvolden and von Huene, 1985). The positive results of that study warranted making a three-dimensional study of 10 gridded multichannel seismic records reprocessed to image deeper parts of the Aleutian subduction zone. The organic matter in 40 samples from DSDP cores and six USGS dredges were analyzed.

The grid of seismic records off southern Kodiak Island, processed with advanced techniques, constrains the volume of sediment subducted at the Aleutian Trench to about $\pm$ 20%. The great volume of sediment subducting at the trench, despite containing only background levels of live carbon, produces 3 ± 1 km^3 of gas per km along the trench in the 6 MY-long history of the present tectonic system. We have ignored previously stored gas in our estimate. The potential volume of gas generated appears sufficiently large to source a major trapping structure within the zone of maximum gas generation and release. The thermal window for the generation of methane is estimated to lie in the mid-slope area. Some potential trapping structures, indicated by closure of depth contours, are located on the decollement surface in the mid-

slope area. A major question concerns reservoir conditions. Brite-spot analysis in the mid-slope area suggests some accumulation of fluids and/or gas in trapping structures. Thus, the prospects for future resource potential are sufficient to warrant continuing the study.

ACCOMPLISHMENTS

- Reprocessed 12 seismic reflection records in the southern grid of the USGS Aleutian Trench data set.
- Interpreted seismic records. Developed a comprehensive velocity model from refraction and reflection data for conversion to depth.
- Converted time sections to depth sections and illustrated interpreted sections in line drawing format.
- Made maps of the depth of the basement surface, decollement, and subducted and accreted sediment thickness. Computed potential amount of gas generated.
- Made an analysis of amplitude and phase anomalies thereby locating areas of concentrated fluid and/or gas.

ARTICLES AND PRESENTATIONS

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DEEP INVESTIGATIVE GEOPHYSICAL STUDIES

INTERAGENCY AGREEMENT NUMBER DE-A121-83MC20422, TASK NO. 4

AGENCY U.S. GEOLOGICAL SURVEY
BOX 25046, MS 964
DENVER FEDERAL CENTER, DENVER, CO 80225

AGENCY COORDINATOR: John Roen, USGS

PRINCIPAL INVESTIGATOR: William D. Stanley, USGS

METC PROJECT MANAGER: William J. Gwilliam, DOE/METC

PERIOD OF PERFORMANCE: Continuing

ABSTRACT

The focus of the research under this task is the study of fossil and active subduction zones using deep investigative geophysical methods to assess the potential for deep sourced gas in deeply emplaced sedimentary packages. The crust of the western U.S. Cordillera is composed of sedimentary units deposited in forearc environments, associated oceanic crust, and volcanic and intrusive rocks associated with the magmatic arcs of present and past subduction zones. The subduction zone units have widely differing geophysical properties and can be mapped to locate regions favorable for the occurrence of deep sourced methane. The electrical resistivity of the prospective sedimentary packages varies most widely of the physical properties, but components of oceanic crust associated with the forearc sedimentary rocks have high magnetizations and densities. Thus, deep electromagnetic soundings using the magnetotelluric (MT) method have been employed to study the resistivities of possible deep basin rocks and other geophysical data such as magnetic, gravity, and seismic data have been employed in a integrated manner to define prospective areas of deep source gas.

ACCOMPLISHMENTS

- Discovered and mapped a major southern Washington Cascades conductor (SWCC) which is interpreted to be a 7-20 km thick sequence of late Cretaceous-early Tertiary marine sedimentary rocks which were compressed and partially subducted during a major accretionary episode in the Eocene.

- Delineated a suture zone in northcentral Washington consisting of thick marine sedimentary rocks in the Methow Trough structural feature. The marine rocks have thicknesses of over 10 km and appear to have been thrust beneath crystalline rocks on the east margin.

- Found that a regionally large flysch basin in Alaska consisting largely of black shales has been collapsed by accretion of a large oceanic rift complex and partially emplaced beneath older rocks in the central Alaska Range near Mt. McKinley.

- Initiated geophysical studies of the Mist gas field in northwestern Oregon with preliminary MT soundings and magnetic mapping of bordering accretionary units.

- Assisted in planning deep reflection seismic surveys in the area of the SWCC and Mist gas fields.

Future plans include integration of the MT, gravity, and magnetic data with the proposed deep seismic line in southwestern Washington and an in-depth study of the Mist gas field in northwestern Oregon where deeply sourced gas is being produced from relatively shallow reservoirs. This field is in Eocene marine sediments in a basin between two components of an accreted seamount complex. In addition, the MT surveys in Alaska will be integrated with similar studies proceeding under a USGS program called the Trans Alaska Crustal Transect (TACT). This research has located structures similar to those mapped further to the west under the Deep Source Gas DOE program.

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DEEP SEISMIC REFLECTION STUDIES IN THE PACIFIC NORTHWEST

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ABSTRACT

Plans for a deep, multichannel seismic reflection survey in the Pacific Northwest are discussed. This study forms part of deep gas research in this region which is designed to evaluate the deep gas potential of this area. Investigations of the history, geologic and geophysical nature, and hydrocarbon-generating potential of deep rocks in the Pacific Northwest are ongoing, and these results are also described.

The seismic reflection profile will extend from Mist gas field, northwest Oregon, east-northeasterly into Washington, and will transect an area in which an electrical conductivity anomaly has been mapped in western Washington. The large volume of rocks responsible for the anomaly has been modeled to extend from depths of 5 km and is interpreted to most likely represent marine sedimentary sequences. The planned line will be approximately 150 km in length, and objectives of the survey are to: 1) seismically characterize the deep, highly conductive rocks using 15 second records, 2) identify midcrustal bright spots which may represent deep fluids, 3) identify possible deep fluid migration pathways, and 4) examine the relationships which exist between Mist gas field in the Oregon Coast Range, the Puget-Willamette basin, and the deep rocks responsible for the conductivity anomaly in western Washington.

Ancillary studies include regional tectonic and basin reconstructions, lineament analyses, and hydrocarbon source rock studies in the Pacific Northwest. Reconstructions suggest that the deep sequences responsible for the conductivity anomaly may be a result of Tertiary rifting, or may have formed as part of a Late Mesozoic or Tertiary forearc or marginal basin. Lineament studies are used to search for structures related to the speculative deep basin. Our investigations indicate that hydrocarbon source rocks do occur in the Pacific Northwest and are associated with a variety of depositional and tectonic environments.

DETECTION/DIFFERENTIATION SYSTEM DEVELOPMENT FOR DEEP SOURCE GASES

CONTRACT NUMBER:	DE-AC21-84MC21131
CONTRACTOR:	Global Geochemistry Corporation 6919 Eton Avenue Canoga Park, CA 91303
CONTRACTOR PROJECT MANAGER:	Dr. Alan W.A. Jeffrey
PRINCIPAL INVESTIGATORS:	Dr. Alan W.A. Jeffrey Dr. I.R. Kaplan Professor Harmon Craig
METC PROJECT MANAGER:	W.J. Gwilliam
PERIOD OF PERFORMANCE:	October 1, 1984 to December 31, 1985 (Phase I)

ABSTRACT

Phase I of this project was designed to collect and analyze hydrocarbon gases from three major sources: deep sedimentary basins, abiogenic, and subducted sediments. Results of the analytical scheme have been used to differentiate subduction zone gases from gases of deep sedimentary or mantle origins. One of the major diagnostic tests is the ratio $^{3}He/^{4}He$, an unequivocal indicator of mantle contribution. Gases were collected and analyzed from the Permian Basin, West Texas, a major deep sedimentary basin, and Iceland, where mantle gases are released into the crust at a spreading ridge. Subduction zone gases were collected in two groups: geothermal gases from volcanic arcs in the Philippines, New Zealand and Alaska, and hydrocarbon production gases from forearc and backarc locations in Taiwan, New Zealand, Alaska, Barbados, Indonesia and the Philippines.

Deep gases from the Permian Basin are composed predominantly of methane, derived from the maturity related decomposition of sedimentary organic matter, and carbon dioxide, from thermal decomposition of sedimentary carbonates. $^{3}He/^{4}He$ ratios are low, dominated by ^{4}He from a crustal radiogenic source, although significantly higher ratios in carbon dioxide dominated gases are probably related to past magmatic activity. Gases from Iceland have much higher $^{3}He/^{4}He$ ratios, dominated by ^{3}He from the mantle. Methane is a minor component in these gases, and is probably associated with the mantle input. Gases from subduction zones have intermediate $^{3}He/^{4}He$ ratios, indicating input from both mantle and crustal sources. Methane in these gases ranges from insignificant to a major component and is also related to the relative inputs from mantle and crustal sources.

Production gases from subduction zones are especially significant: most commercial accumulations of hydrocarbons in subduction zones have a significant ^3He content. This contrasts with uniformly lower ^3He contents in gases not associated with subduction zones. Heating of subducted sediments by mantle volatiles is a possible source of both hydrocarbons and ^3He in subduction zone gases. However, the source of the hydrocarbons in these gases remains in doubt since the present data are unable to differentiate hydrocarbons in production gases from deep sedimentary basins and subduction zones. This may indicate that hydrocarbon formation mechanisms are similar in sedimentary basin and subduction environments, and that gases from the two sources may be differentiated solely through secondary components, such as helium and CO_2.

ACCOMPLISHMENTS

- Documented the widespread input of mantle volatiles to hydrocarbon production gases at subduction zones which differentiates these gases from those of deep sedimentary basin origin

- In the Philippines, neighboring gas fields have strikingly different mantle volatile contents, indicating a localized mechanism of injection.

- Striking differences in $CH_4/^3He$ ratios in geothermal gases from eastern and western Philippines may result from differences in subduction activity affecting transport of organic carbon to the magmatic arc.

- Identified a minor input of mantle volatiles into Permian Basin production gases, probably related to a past magmatic event.

PRESENTATIONS

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NOTES

SESSION 3A

POSTER SESSION

The Unconventional Gas Recovery (UGR) Program is directed toward the development of advanced technologies for recovering gas from large, currently uneconomically recoverable resources where the geology is complex and the production mechanisms are not well understood. Within the UGR Program, primary targets for investigation are:

- Western Gas Sands
- Eastern Gas Shales
- Coalbed Methane
- Gas Hydrates
- Deep Source Gas

For the achievement of this goal, a series of interrelated technology development steps are required, some sponsored by DOE, some by other government agencies, and some by the private sector. These include basic and applied research and development, proof-of-concept activities, first-of-a-kind field tests, and associated commercial scale activity. Activities associated with DOE's UGR Program goal are designed to achieve one or more of the following:

- Fundamental understanding of the geologic resource.
- Expanded technically recoverable resource base.
- Maximized recovery efficiency.

These activities have the objective of assisting industry in overcoming the technical, economic, and environmental barriers which substantially limit development of the nation's UGR resources by present technologies to a very small fraction of their potential as a domestic source of gas. A stronger technical and environmental data base permits industry and government to more accurately assess the performance and costs of alternative resource process concepts and to conduct the subsequent technology development steps leading to commercialization.

Within the UGR Program, the highest priority research is that required to generate data essential to the private sector's decision-making process leading to field tests and ultimately to implementation of commercial projects. In support of this objective, geological studies have quantified the in place gas resource to be quite large and the more favorable areas warranting test wells have been identified for a number of basins. Experimental wells have served to define the needed improvements in well completion and stimulation activities to unlock a portion of these resources. Detailed engineering studies, combined with field experience, are building an improved knowledge base for establishing the recoverable gas from these resources as a function of advanced technology.

All efforts are focused toward quantifying the risks and uncertainties associated with these resources so that when the demand/market warrant renewed drilling, sufficient information will be available on where to drill, how to extract, and expected payoff to consider unconventional resources as just another reservoir.

GEOSCIENCES

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ABSTRACT

The Geosciences Research Branch at the Morgantown Energy Technology Center has developed a versatile analytical capability to characterize petroleum reservoirs. The systems installed and techniques employed are compatible with those in use by industry and government agencies involved in petroleum exploration, research, and production. This capability is currently being applied to projects in the Unconventional Gas Resources program and, in particular, applications to the Gas Hydrates, Deep Source Gas, and Western Tight Sands projects are illustrated. The analyses highlighted in the posters include computerized well log analysis using Energy Systems software, thermalytic hydrocarbon analysis using Delsi's instrument, statistical and graphical analyses of geoscientific data using Petroleum Information's Geologic Analysis System, as well as METC-developed software, lineament analysis, mechanical testing, and automatic image analysis applied to geologic materials. The information acquired by these techniques is used to quantitatively define petroleum reservoir geometry and rock characteristics for modeling future production from these unique petroleum occurrences.

by

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ABSTRACT

Large quantities of natural gas in conventional and unconventional resources are located in Alaska, and smaller quantities are found in other locations in the U.S. that are remote from gathering systems. At present, these resources cannot be effectively utilized. The economics of reinjecting associated gas produced with crude oil on the North Slope are getting worse, and other near-term options such as the Alaskan Natural Gas Transportation System (ANGTS) or conversion to LNG do not appear promising. Remote sources of natural gas could be more effectively utilized if the gas could be converted to an easily transportable liquid fuel such as gasoline. Conventional conversion technology using steam reforming to convert natural gas to synthesis gas (CO and H_2), followed by methanol synthesis and conversion of methanol to gasoline, is economically not competitive with gasoline from crude oil at present oil prices. High construction costs in remote areas such as Alaska's North Slope further add to conversion costs. METC systems studies have examined the potential for new conversion technology and have concluded that a process consisting of catalytic partial oxidation of natural gas to olefins, followed by conversion of olefins to gasoline, would be significantly less costly than the conventional process. However, for this new process to be economic at present-day oil prices, improved catalysts are needed for the first step in this process in which methane is converted to ethylene and other more reactive compounds which then can be converted to gasoline. In addition, there is potential for further cost reduction of conversion technology through development of simplified partial oxidation-based processes and through R&D into homogeneous or biologically-derived catalytic processes. METC has initiated a laboratory research program to identify the key mechanisms in the catalytic "activation" step, which converts methane to more reactive chemicals, and to evaluate promising catalyst materials to improve the efficiency of this conversion. Advanced surface science techniques such as X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) are used for mechanistic studies, and a flow reactor is used to screen catalysts and test new concepts.

PLASMA CHEMISTRY

FTPA NUMBER: AES/84-1

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CONTRACTOR PROJECT MANAGER: Francis T. Finch
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PRINCIPAL INVESTIGATOR: Wayne C. Danen
FTS: 843-7121

METC PROJECT MANAGER: Rodney D. Malone

PERIOD OF PERFORMANCE: May 1, 1984 to Sept. 30, 1987

ABSTRACT

The immediate objective of this research is to develop a comprehensive understanding of the fundamental mechanism and kinetics of the partial oxidation of methane directly to methanol for use as the basis for the design of a process. The goal is to achieve a sufficiently high yield that an operable and economically viable process can be applied to conversion of remote natural gas to liquids for transportation to markets in the United States. The process will be kinetically controlled, with unconventional initiation and termination.

Scientifically, the essence of the project is to control the direct partial oxidation of methane to produce useful yields of methanol:

$$CH_4 + 1/2\ O_2 \text{ ---> } CH_3OH.$$

It is crucial that complete oxidation to the thermodynamically stable products, carbon dioxide and water, be avoided. The detailed chemistry of the reactive intermediates and of the possible reaction pathways under various conditions must be understood in order to specify the reaction parameters necessary to obtain high yields of methanol. We are employing an integrated, multidisciplinary approach using state-of-the-art theoretical and experimental tools including computer kinetic modeling, fundamental kinetics measurements, theoretical rate constant calculations, bench-scale reactor experiments, and systems analysis.

Major accomplishments to date include the following:

- Demonstrated scientific proof-of-principle by achieving 70% selectivity for methanol formation for 99:1 CH_4:O_2 mixtures
- Developed a comprehensive kinetic working model with predictive capabilities and identified key reactions and reaction intermediates

- Benchmarked the computer kinetic model against real experiments in a microprocessor controlled bench-scale static reactor
- Predicted experimental conditions for high methane conversion and high methanol selectivity in a flow reactor
- Demonstrated advantages of laser, plasma, and free radical precursor initiation
- Measured removal rate constants for methoxy radical interacting with O_2, CH_4, and a variety of unreactive gases over a wide temperature range
- Developed a general procedure based on RRKM theory for calculation of rate constants of unimolecular reactions over a wide range of temperature and pressure

The current goals of the project are to continue to refine the model and experimental techniques and to investigate means for increasing the overall yield of methanol in a single pass to a level that is economically attractive. Several of methods for achieving high overall yields have been identified and will be systematically investigated.

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M. Burshears, K. Dominic

ABSTRACT

A two-phase, three-dimensional numerical model was developed to simulate the dissociation and formation of hydrates when a conventional gas reservoir is in contact with hydrates. This model was developed in order to address fundamental questions regarding the feasibilty of the dissociation of hydrates due to the depressurization which accompanies the production of the conventional gas reservoir. The major implications of the simulation are quite favorable, suggesting that massive hydrate can be dissociated at appreciable rates without an external heat energy source. These results support the continued evaluation of gas hydrates as a potential resource, and indicate a need for model validation.

Due to scant documentation of the production of gas hydrates in the literature, the validation of this simulator was not possible with conventional methods; an alternative, three stage method of testing was devised. Existing resources were used in two parts of this testing. The third step required a laboratory simulation of the behavior of a gas hydrate reservoir during pressure reduction and gas extraction. In the Gas Hydrates Laboratory, an experiment was designed to produce gas from dissociation of synthetic methane hydrate by depressurization. Following initial pressure reduction to initiate dissociation, gas was produced from this bench-scale reservoir at constant pressure. Flow rate was allowed to vary. Dissociation proceeded in pulses which steadily decreased in magnitude as the gas in the reservoir was depleted. The flow decline curves generated in 23 production cycles conform to two distinctive shapes. The curves possess features in common with both hydrate field data and conventional gas reservoir data. These data have been used to test and refine the simulator.

The testing indicates that the model is a useful numerical representation of the dissociation of massive hydrate when subjected to pressure reduction. This effort has identified a weakness in the simulator, i.e., that it does not address kinetics. Future work should include a quantification of the accuracy associated with the model's predictions of the behavior of the bench scale reservoir. This statistical analysis, along with laboratory confirmation of the thermal and dissociation constants, would complete the model validation. Additionally, a need for an involved study of the kinetics of hydrate dissociation/formation processes, with complementary model enhancement, is indicated.

By

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J. S. Hancock,[2] J. H. Dean,[2] C. R. Regenhardt,[2]
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ABSTRACT

The U.S. Department of Energy, Morgantown Energy Technology Center has recently completed four reservoir simulation studies involved with predicting gas production from Devonian shale and lenticular formations in western Colorado.

The first study simulated the effect of using horizontal wells to increase the recovery efficiency of shale gas from two specific sites: Wayne County, West Virginia, where vertical well gas production has been historically high and no permeability anisotropy is thought to exist, and Meigs County, Ohio, an area with a history of moderate gas production and a calculated permeability anisotropy of approximately 8:1. In this study, a three-dimensional, dual-porosity reservoir simulator was used to characterize the study areas after sensitivity analyses were made to determine those parameters significant in determining gas production profiles. Once the study areas were characterized, the 20-year production profile for a 2,000-foot (610-meter) horizontal well was simulated for three well locations in Wayne County and one location in Meigs County.

The performance of several vertical wells was also simulated and compared to that of their corresponding horizontal wells in Wayne County. Results of the simulation showed that a horizontal well could produce 7 to 10 times more gas than a vertical well placed at the same location for the Wayne County site. In the Meigs County area, the study showed that permeability anisotropy is an important factor in determining the orientation that a horizontal well should be drilled. Furthermore, the study concluded that horizontal wells are more efficient than vertical wells in producing Devonian shale gas from a fixed volume of rock.

The second study investigated using infill drilling as a production strategy to increase the reserve base of the Devonian shale formations in Ohio, Kentucky, and West Virginia. The study utilized data that has evolved in the Eastern Gas Shales research program to compile gas-in-place estimates and analyze key production mechanisms. Each state was partitioned into areas according to the key geological parameters and tectonophysics that establish the natural stress

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and fracture regimes. Within these partitioned areas, an infill drilling simulation study was conducted to determine the impact of reduced well spacing on 40-year cumulative gas production. In this approach, 1, 3, and 5 infill wells were simulated randomly in a field of 5 existing wells which had been producing for 20 years. After 20 years of well production, the individual simulated infill well recovery was evaluated. Results indicated the infill drilling strategy was appropriate for two out of four Kentucky partitions and two out of six West Virginia partitions. Infill drilling was not feasible in any of the six Ohio partitions at current gas prices. Additionally, a case study was completed in West Virginia to compare actual field data with simulations. The study site is located in a noncandidate infill drilling partition. Infill wells were simulated in an existing field randomly and in an area of high flow capacity. Results indicate that 50 percent more gas may be recovered over a 10-year period if infill wells are drilled in the more geologically favorable area of a field. Results also indicate that noncandidate partitions may have infill drilling potential if simulated geologic reference is used for well site selection.

The third study focused on natural gas occurrences and reservoir characterization in the assessment of the production potential in the Piceance Creek Basin (Garfield County, Colorado). This basin has reservoirs with lenticular sands that are characterized as having low porosities, low permeabilities, and relatively high water saturations. One such horizon is the Mesaverde group which consists of discontinuous sandstone lenses distributed within a shale matrix and is present throughout the Piceance Creek Basin. Prior studies of the commercial Rulison field located in the south-central portion of the basin in Garfield County indicated that compressional forces created an anticlinal nose aligned northwest to southeast through part of the field; these forces created a conductive natural fracture system that enhances the permeability of the Mesaverde. This study shows a relationship between the Rulison field and an area south of Rulison, which encompasses approximately 36 square miles (93.2 km^2). The area has been sparsely drilled to date (averaging one well per two sections and nonuniformly spaced); thus, the possibility exists for further commercial development through infill drilling. The southern Rulison area is characterized in structure, percent sand, and critical reservoir parameters including permeability. Production rates, cumulative gas production, and drilling and completion data are used to infer permeabilities by history matching, using a dual porosity, dual permeability reservoir simulator. Results include a reservoir description of the area with economic evaluations of several investment scenarios in order to assess the economic feasibility of exploiting the potential resource.

The fourth study investigated using multidrain wells to recover a larger percentage of gas from lenticular reservoirs in western Colorado than is currently being recovered with two vertical wells per section for Mesaverde completion. A multidrain well (i.e., two additional boreholes at an angle to the vertical) will intersect more lenses which causes larger volumes of gas to be produced. Analysis shows that a multidrain well can produce up to 200 percent more gas than a vertical well at a cost of 133 percent more than that of a vertical well.

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SESSION 4A

WESTERN GAS SANDS

Chairman: Karl-Heinz Frohne, METC

OVERVIEW

WESTERN GAS SANDS

by

Karl-Heinz Frohne[1]

Western gas sands research is conducted by the U.S. Department of Energy's (DOE) Morgantown Energy Technology Center to encourage the development of very low permeability, lenticular gas sands in the western U.S. This research is an integral part of DOE's Unconventional Gas Recovery Program which is a multi-disciplinary effort to develop the technology for producing natural gas from resources that have been classified as unconventional because of unique geologies and production mechanisms.

The purpose of this research is to demonstrate to private industry the feasibility of economically producing natural gas from these low-permeability reservoirs. The reservoirs, which are found within a resource area that covers 311,000 square miles, contain an estimated 925 trillion cubic feet (Tcf) of gas-in-place.

Two broad research goals have been defined: (1) to reduce the uncertainty of the reservoir production potential and (2) to improve the extraction technology. These goals are being pursued by conducting research and encouraging industrial efforts to develop the necessary technology. These efforts involve the following activities:

- Conducting fundamental research into the nature of tight lenticular gas sands and the technologies for diagnosing and producing them.
- Developing and verifying the technology for effective gas production.
- Promoting the transfer of research products and technology advances to the gas industry in usable forms.

Integrated geologic studies of three depositional basins that contain tight lenticular sandstone units have also been pursued as part of this new effort. These lenticular sands were selected by DOE as priority research targets because of the size of the resource potential and the many technical and economic questions blocking industry development.

Aside from the current industry-wide recession due to depressed energy product prices, industry has been reluctant to risk R&D funds on any but the geologically most favorable unconventional gas resources; this is a key factor that precludes the development of tight gas formations. To make these potentially valuable national resources more attractive, the technological risks must be reduced.

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Two major technical issues warrant attention: (1) the location and magnitude of the resource and the size of the recoverable reserves must be determined and (2) current extraction technology, which now can be used to recover only a small portion of these resources, must be demonstrably improved if gas from tight sands is to compete with cheaper gas from conventional resources. The first problem that must be faced to determine the magnitude of a tight gas resource is to define the gross geology of the reservoirs. When this is resolved, the part of the geologic resource base that actually contains recoverable gas can then be determined. Research must provide the ability to predict where the producible gas is concentrated and how efficiently it can be recovered.

Currently, geologic research is aimed at providing a comprehensive analysis of the Greater Green River Basin, the second of the three priority basins to be so evaluated. Geologic support to the multiwell experiment (MWX) in western Colorado is also being performed, both on and off site.

The current focus in basic research is to develop an understanding of tight sands and to establish and verify a predictive capability for reservoir and stimulation performance. This research also provides diagnostic support to field experiments. Laboratory research is performed on fracturing materials and their effects on geologic formations, basic reservoir properties of tight sandstones, and fracture mechanics. Specific efforts include the development of a comprehensive technical data base for tight sandstones, long-term development and verification of reservoir and stimulation simulators, and the development and field application of diagnostic instrumentation.

Field verification activities substantiate results that are obtained from laboratory and modeling studies, and help make extraction technology and predictions of recovery efficiency more reliable. To assist in this production research effort, a three-well field laboratory was installed in the Piceance Basin in 1983. Scheduled technical research at this MWX site includes the systematic assessment of reservoir behavior and stimulation performance in the lenticular Mesaverde Group reservoirs by performing specific field tests. Well tests that are being conducted include three-well production testing and fully instrumented simulation experiments on the characterized formation to determine stimulation efficiency. Such MWX research cycles have been completed in the Paludal zone of the Mesaverde Group, a gas-bearing lenticular interval of high geological complexity and in the Coastal zone where a comprehensive, multi-part stimulation/reservoir performance experiment has been executed. Current activities are now centered on the Fluvial zone which is geologically representative of the bulk of the Mesaverde Group.

Stimulation research in an in situ setting which serves as a verification interface between the laboratory and the field has been performed at the Nevada Test Site. Field operations have been completed in 1986 on both semicommercial-scale hydraulic and high energy gas-fracturing (HEGF) experiments. Test data have been gathered through mineback operations that permit direct inspection of performance. HEGF results have been evaluated and show that this stimulation process which is independent of formation stresses can be safely and effectively carried out in cased wells. The gas frac process has been commercialized to some degree and has recently been used at the multiwell site as a formation breakdown technique. Experimental data from the hydraulic fracturing trial is still being analyzed.

To date, the following tentative conclusions have been formulated:

- The permeability of the tight gas sands can be as much as three to four orders of magnitude lower than that of conventional gas deposits.
- Nineteen (19) western geologic basins and trends have been identified that contain significant volumes of tight gas.
- Gas resources in the priority geologic basins have been estimated as follows:
  - Piceance Basin, 420 Tcf.
  - Greater Green River Basin, 136 Tcf.
  - Uinta Basin, 20 Tcf.
- The critical parameters for successfully developing tight sandstone resources are (1) the presence of natural fractures within a reservoir and (2) the effective propped length of hydraulically induced fractures.
- Stimulation technology is presently insufficient to efficiently recover gas from lenticular tight reservoirs.

With advancements in technology and some imaginative solutions, tight gas resources can double our present natural gas reserves. In addition, these resources can, in effect, provide the time the U.S. needs to make the transition from dependence on nonrenewable fossil fuels to alternative nonfossil sources.

TIGHT GAS RESERVOIR CHARACTERIZATION - GREATER GREEN RIVER BASIN

CONTRACT NUMBER: DE-A121-83MC20422

CONTRACTOR: U.S. Geological Survey
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PRINCIPAL INVESTIGATORS: Ben E. Law
Charles W. Spencer
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METC PROJECT MANAGER: Karl-Heinz Frohne

PERIOD OF PERFORMANCE: October 1, 1986 through July 31, 1987

ABSTRACT

The main objective of USGS work in the Greater Green River basin is to conduct geologic research on low-permeability gas reservoirs in order to gain an improved understanding of the nature of these unconventional gas accumulations. Since the inception of the program, USGS research has focused on the characterization of tight gas reservoir systems and the importance of abnormal pore pressures. The relationship between abnormal pressure and the occurrence of gas-saturated reservoirs has enabled us to identify, more accurately, the stratigraphic limits of tight gas reservoirs and has facilitated exploration, exploitation, and resource assessment.

During the reporting period, we have continued to investigate the processes related to the development of abnormal pressures. Thermal maturity investigations have revealed evidence of segmented paleothermal gradients which we have interpreted to be the result of thermal perturbations related to the origin of abnormal pressures. This type of work has enabled us to formulate a geologic rationale for the resource assessment of tight gas reservoirs in the Pinedale anticline of the northern Green River basin and will eventually be incorporated into the resource assessment of the entire basin.

ACCOMPLISHMENTS

- Completed the vitrinite reflectance analysis of samples from the Greater Green River basin. The data set includes over 1,000 values from about 400 wells.
- Completed a new structure contour map of the Greater Green River basin.
- Conducted x-ray diffraction analyses of several samples from two deep wells in the northern part of the Green River basin and from the Upper Cretaceous Almond Formation in the Great Divide and Washakie basins.

° Core analyses were conducted on samples from the Almond Formation. The analyses consisted of klinkenberg permeability, porosity, grain density, and bulk density. Additional analyses include the effects of confining pressure on permeability and porosity and mercury injection capillary pressure tests.

° Preparation of a multi-chaptered volume comparing geologic relationships in the Pinedale and MWX areas.

° Completion of the gas resource assessment in the Pinedale anticline.

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UNCONVENTIONAL GAS RECOVERY
CONTRACTORS MEETING

PROJECT SYNOPSIS

CONTRACT TITLE:	Rock Matrix and Fracture Analysis of Flow in Western Tight Gas Sands
CONTRACT NUMBER:	DE-AC21-84MC21179
CONTRACTOR:	New Mexico Institute of Mining and Technology
ADDRESS:	New Mexico Petroleum Recovery Research Center
CITY,STATE,ZIP:	Socorro, NM 87801
TELEPHONE:	(505) 835-5403
PROGRAM MANAGER (CONTRACTOR):	Joseph J. Taber
PRINCIPAL INVESTIGATOR:	Norman R. Morrow
METC PROJECT MANAGER:	Karl-Heinz Frohne
PERIOD OF PERFORMANCE:	June 1984 - June 1985

ABSTRACT

The objective of this project is to develop reliable core analysis techniques for tight gas sands properties that are essential to proper formation evaluation. The study is mainly concerned with the dependence of flow in tight gas sands on water saturation and confining pressure. This dependency is to be related to the detailed pore structure of tight sands as typified by cores recovered in the Multi-Well Experiment.

WORK PERFORMED

- Advanced Core Analysis

Screening tests of pressure sensitivity for all Multi-Well cores on hand are complete. The tests involved measurement of Klinkenberg permeabilities at overburden pressures of 500 psi and 5000 psi for first unloading. Reduction in permeability with overburden pressure expressed as $K_{\infty,500}/K_{\infty,5000}$ ranged from as low as 1.5 to as high as 45. Cores representing a wide range of sensitivity are now being studied in detail.

- Flow Properties of Natural Fractures

We continue to measure relationships between permeability and confining pressure for core samples containing calcite-filled fractures and for neighboring matrix material from a given whole core sample. Results to date show that calcite-filled fractures act neither as severe permeability barriers for flow across the cement nor as highly conductive paths along the fractures.

In order to determine whether the matrix or the fracture carried the bulk of the gas flow a technique for detecting relative differences in gas flow over a core cross-section was developed. This involved injecting a small

amount of hydrogen sulfide in the inlet gas stream and detecting its distribution at the outflow face by means of moist filter paper which had been soaked in AgCl solution.

- Heterogeneity of Flow in Tight Sand Matrix

More detailed understanding of gas flow in tight sands is being gained through study of heterogeneity in flow within the rock matrix. Thermal conductivity, bubble evolution, soap films and the chemical detection methods have been used to detect flow heterogeneities. A core holder has been designed for investigating the distribution of flow heterogeneities and the effects of overburden on flow rates at sites of high gas flow. In general sites of high gas flow are less pressure sensitive than the matrix as a whole.

- Porosity

We have observed that porosities from thin sections are generally lower than those determined by other measurements of pore volume. A comparative study of commercially prepared slides showed that incomplete impregnation of resin is the most likely cause of low porosity measurements. Porosity originating from dissolution of unstable grains accounts for most of the pore-space volume in tight sands. Casts of solution pores have been prepared by injection of styrene followed by polymerization and acid leaching. Electron micrographs reveal, in detail, the variety of structure of these solution pores.

- Capillary Pressures by High-Speed Centrifuge

High-speed centrifuge measurements have been used to determine capillary pressure versus saturation relationships for selected core samples from the coastal, paludal, paralic and fluvial zones of MWX1, MWX2, and MWX3. Application of the Hassler-Brunner model to interpretation of the raw centrifuge data for tight sands has been investigated in detail. Desorption iostherms for water provided extension of capillary pressure curves to extremely high pressures.

ACCOMPLISHMENTS

- 35 Multi-Well cores have been characterized by sensitivity of permeability to overburden pressure.
- Measurements on 10 Multi-Well cores containing mineralized fractures are 50% complete.
- Effects of overburden pressure and water saturation on gas permeability have been determined together with estimates of relative permeability to water.
- Capillary pressures by high-speed centrifuge have been extended to very high pressures through measurement of desorption isotherms for water.
- Surface area measurements by N_2 adsorption have been completed for over 50 Multi-Well samples.

- Detailed structure of individual solution pores has been revealed through electron micrographs of pore casts.

- Techniques for investigating flow heterogeneities in the rock matrix have been developed.

FUTURE WORK

- Advanced core analysis. Cores representing a wide range of pressure sensitivity will be used in a detailed study of the effects of water saturation and overburden pressure. Fractured core flow properties will be compared with those for neighboring matrix material.

- Heterogeneity of gas flow in the rock matrix will be investigated by new techniques.

- Pore structure will be investigated by microscopy and through capillary pressure, adsorption isotherm and surface area measurements.

PUBLICATIONS AND PRESENTATIONS

1. Brower, K.R. and Morrow, N.R., "Fluid Flow in Cracks as Related to Low Permeability Gas Sands," Soc. Pet. Eng. J., (April 1985) 191-201.

2. Wei, K., Morrow, N.R., and Brower, K.R., "Effect of Fluid, Confining Pressure, and Temperature on Absolute Permeabilities of Low Permeability Sandstones," SPE 13093 presented at 59th Annual Technical Conference and Exhibition, Houston, TX, Sept. 16-19, 1984; Soc. Pet. Eng. J., In Press.

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FRACTURING MATERIALS RESEARCH

CONTRACT NUMBER: Sandia Contract No. 95-4340

CONTRACTOR: IIT Research Institute
National Institute for Petroleum and Energy Research
Bartlesville, OK 74005

CONTRACTOR PROJECT MANAGER: Dr. A. R. Sattler

PRINCIPAL INVESTIGATORS: C. J. Raible
Dr. B. L. Gall

METC PROJECT MANAGER: K-H. Frohne

PERIOD OF PERFORMANCE: October 1985 to September 1987

ABSTRACT

The objective of this fracturing materials research project is to support the stimulation of low-permeability lenticular reservoirs for the DOE MWX. This work focuses on determining the role played by fracturing materials which contribute to formation damage and restriction of gas flow through a fracture to the wellbore. Emphasis has been placed on examination of fracturing materials and their interaction with MWX reservoir rock in the following areas:

- reservoir rock and natural fracture damage caused by fracturing fluids;
- fluid leak-off through matrix and fractures, including implications for fracture design;
- fracturing fluid polymer studies; and
- damage to proppant pack conductivity caused by polymer damage, stress, and embedment.

During the reporting period, these studies have shown that fracturing fluid damage to MWX reservoir rocks is largely transitory, a result of increased liquid saturations. Cleanup may be slow and depends on formation properties such as permeability, capillary pressure, and gas production. Polymer damage to natural fractures, however, can be significant. Effective permeability of natural fractures may be reduced as much as 90 percent by trapped polymer gels in the fractures.

In laboratory studies, fluid leak-off through the low-permeability matrix and fractures does not follow the commonly used $time^{\frac{1}{2}}$ relationship. Our experimental results indicate that fluid leak-off with MWX core is more often closely represented by a $time^{3/4}$ relationship. Use of fluid leak-off coefficients for fracture design calculated from a $time^{\frac{1}{2}}$ function may underestimate total fluid loss to the formation by 15 to 40 percent. Efforts are underway to develop improved fluid leak-off coefficients from laboratory data for more accurate predictions.

Polymer degradation studies have shown that biopolymer used in the MWX coastal

stimulation is difficult to degrade. As a result, a special braker system has been designed by the service company. This new breaker system appears to improve polymer hydration, produces a more homogenous gel, and reduces gel viscosity at formation temperature.

The biopolymer can be flushed from a proppant pack under stress if brine is used as a test fluid. Only a small decrease in permeability is observed using brine as a cleanup fluid; however, a significant reduction in gas permeability results when gas is used to clean up a proppant pack. Many pore volumes of gas are required to dry the polymer and maximize proppant pack permeability.

Finally, MWX sands and shales should be capable of being successfully propped. Long term embedment studies show a small reduction in fracture width.

ACCOMPLISHMENTS

- Supported mechanisms suggested for transitory formation damage in the Paludal Zone MWX stimulation.
- Demonstrated an improved method for estimating fluid leak-off into low permeability formations from laboratory leak-off tests.
- Determined the effects of polymer damage in a propped fracture.
- Related the degree of polymer degradation to flow impairment and determined the need for improved breaker systems to improve fluid return and prevent fracture damage.
- Recommended production practices to minimize permanent conductivity damage to propped fractures.

ARTICLES AND PRESENTATIONS

Gall, B. L. and Raible, C. J., The Use of Size Exclusion Chromatography To Study the Degradation of Water-Soluble Polymers Used in Hydraulic Fracturing Fluids, presented at the National ACS Meeting, Anaheim, CA., Sept. 1986.

Sattler, A. R., Hudson, P. J., Raible, C. J., Gall, B. L., and Maloney, D. R. Laboratory Studies for the Design and Analysis of Hydraulic Fractured in Lenticular, Tight Gas Reservoirs, SPE Paper 15245 presented at the 1986 Unconventional Gas Technology Symposium, Louisville, KY, May 18-21.

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TWO-PHASE FLOW IN TIGHT SANDS

CONTRACT NUMBER: DE-FG21-85MC22000

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PRINCIPAL INVESTIGATOR: Prasan Chowdiah

METC PROJECT MANAGER: Karl-Heinz Frohne

PERIOD OF PERFORMANCE: September 30, 1985 to September 29, 1987

ABSTRACT

Most conventional core analysis techniques used for high permeability sandstones are not readily applicable to tight sandstones, primarily due to the extremely small flow rates and high capillary pressures encountered in these sandstones. The objective of this project is to develop equipment as well as laboratory and analytical techniques for obtaining properties of tight sands that are needed for two-phase computer simulation of production. The experimental work being carried out uses an apparatus (Experimental Tight Rock Apparatus, or ExTRA) which was originally built under funding from the Gas Research Institute (GRI). Emphasis during this project has been on conducting experiments under net stresses representative of in-situ stress levels, and on developing techniques whereby water saturation in the sample can be varied under controlled conditions of drainage or imbibition rather than by evaporation.

Experiments have been designed and conducted for measuring the following properties along a true drainage path at in-situ net confining stress: capillary pressure and gas phase permeability as a function of water saturation, critical gas saturation and permeability to water. Besides demonstrating the feasibility of the experimental techniques, the results obtained on a number of Mesaverde sandstones have yielded useful conclusions when compared with data from mercury porosimetry and from core analysis where evaporation was used to vary water saturation. The results emphasize the need to correct unconfined sample mercury penetration capillary pressure data for confining stress effects. Also, relative permeability curves obtained using the evaporation method are found to display high critical gas saturations of approximately 40% as compared to less than 10% for the true drainage data, suggesting that the evaporation method yield a pore water distribution representative of imbibition. Measured specific water permeabilities have been found to correlate well with dry Klinkenberg permeabilities.

These results are useful in providing correlations or "rules-of-thumb" which can aid in rapid and reliable estimation of capillary pressure and relative permeability curves for tight sands. While most of the data thus far obtained under this project is on Mesaverde sandstone samples from the multiwell experiment, samples from other formations are now being tested. Work during the remaining months of this project is expected to focus on data interpretation techniques, and on the application of results to date for arriving at guidelines regarding the meaningful use of laboratory data as inputs in reservoir simulation.

ACCOMPLISHMENTS

- Developed a technique for making coordinated gas-water capillary pressure and gas phase permeability measurements on tight sands under drainage conditions at in-situ net stress.

- Made capillary pressure measurements on a few tight sand samples at in-situ net confining stress and compared the results with mercury porosimetry data, showing the need to correct unconfined sample data for the effect of confining stress.

- Developed a technique for measuring permeability to water, gas entry capillary pressure, critical gas saturation, and gas phase permeability as a function of water saturation.

- Measured the above properties for a set of Mesaverde tight sandstones and analyzed the data in conjunction with earlier data on these samples when evaporation had been used to vary water saturation. The results showed large differences between the drainage and evaporation data, and provided insight into the differences in pore water distribution in the two methods. Specifically, the results showed that the evaporation data was more representative of an "imbibition" water distribution.

- Made significant progress in developing generalized rules and correlations based on experimental data, to permit rapid and reliable estimation of tight sand reservoir matrix properties from a limited amount of laboratory data.

ARTICLES AND PRESENTATIONS

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Chowdiah, P. 1987. Laboratory Measurements Relevant to Two-Phase Flow in a Tight Gas Sand Matrix. Paper to be presented at the SPE Annual Technical Conference and Exhibition, Dallas, TX, September 27-30.

UNCONVENTIONAL GAS RECOVERY

CONTRACTORS REVIEW MEETING

Morgantown, WV, July 28-29, 1987

Contract Title:	:	Unconventional Gas/Western Gas Sands Research
Contract Number	:	W-7405-ENG-48
Contractor	:	Lawrence Livermore National Laboratory (LLNL) Livermore, CA 94550
Program Manager	:	Francois E. Heuze, (415) 423-0363; FTS: 543-0363
Principal Investigators	:	F. Heuze, R. Shaffer, R. Thorpe
METC Project Managers	:	C. Komar and K-H. Frohne
Period of Performance	:	FY 1986 Continuing in FY 1987.

ABSTRACT

Objective

The objective of the LLNL Western Gas Sands Research is to provide a physical basis for the analysis of stimulation of jointed tight western gas reservoirs. This entails a combined experimental and numerical modeling effort.

Background and Approach

The Western Gas Sands (WGS) subprogram at LLNL is part of the Unconventional Gas Program. Other areas of activities over the past several years have been Eastern Devonian Shale research, and work in support of Coal Bed Methane extraction.

LLNL's approach is to

- develop numerical models (finite elements) of the mechanics of fluid-driven fractures interacting with naturally jointed tight gas reservoirs.
- validate these models by comparison with physical experiments and analytical solutions
- improve the quality of material properties constants input into the calculations by doing research and testing which relates to the in-situ values of such properties.

Program tasks

- development of the transient coupled fracture and flow model FEFFLAP/FAST (ongoing)
- physical models of stimulation of lenses away from wells (ongoing)
- estimation of crack-opening modulus from pressure records (completed).

ACCOMPLISHMENTS

- We have developed a new numerical model which can analyze in 2-D the transient propagation of fluid-driven fractures in jointed tight gas reservoirs. The model can track single and multiple fractures; the medium can be represented as permeable and impermeable. The fluid flow can be dynamic such as with explosive stimulation. This new model is a coupling of the FEFFLAP (LLNL) and FAST (S-Cubed) codes.

- We have started developing the tools for performing laboratory experiments which involve tracking fractures away from a well into and out of lenses. A new flat jack technology has been created for the multi-axial loading system and new embedded sensors have been selected for fracture front tracking. We are in the first year of a 3-year effort.

- We have completed a study describing how bottomhole pressure records from stimulations could be used to estimate the in-situ modulus of reservoir rocks. This work was documented in LLNL report UCID-20995 which provides a very detailed analysis of constant height hydrofractures, and unifies the CGDD and PKN theories into an approximate hybrid CGDD/PKN model; this model can be applied to constant height fractures of arbitrary length/height aspect ratio and arbitrary cross-sectional shape

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Heuze, F. E., Shaffer, R. J., and Ingraffea, A. R. "A Coupled Model for Fluid-Driven Cracks in Jointed Rocks", in Coupled Processes Associated with Nuclear Waste Repositories, (C-F. Tsang, Ed., Academic Press, Orlando, FL), 655-662, 1987.

Lin W. and Heuze, F.E. "Comparison of In-Situ Dynamic Moduli, and Laboratory Moduli of Mesaverde Rocks", Int. J. Rock Mechanics and Mining Science, 1987.

Shaffer, R.J., Heuze, F.E., Thorpe, R.K., Ingraffea, A.R., and Nilson, R.H., "Models of Quasi-Static and Dynamic Fluid-Driven Fracturing in Jointed Rocks", Proc. Int. Conf. of Fracture of Rock and Concrete, Houston, TX, June (Soc. for Exp. Mech.) Also Lawrence Livermore National Laboratory UCRL-94353, Jan. 1987.

Shaffer, R.J., Heuze, F.E., and Nilson, R.H. "Finite Element Models of Hydrofracturing and Gas Fracturing in Jointed Media", Proc. 28th U.S. Symposium on Rock Mechanics, Tucson, AZ., (a. A. Balkema, Boston, MA), June 1987.

Wijesinghe, A.M. "Extended Analysis of Constant-Height Hydraulic Fractures for the Estimation of In-Situ Crack-Opening Modulus from Bottomhole Pressure Records", Lawrence Livermore National Laboratory, UCID-20995, March 1987.

DEVELOPMENT OF A COMPREHENSIVE HYDRAULIC FRACTURE MODEL

CONTRACT NUMBER: DE-AC21-84MC21119

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CONTRACT PROJECT MANAGER: Edmund F. Rybicki, The University of Tulsa

PRINCIPAL INVESTIGATORS: Edmund F. Rybicki, The University of Tulsa
C. Thomas Luiskutty, Oral Roberts University
John Sutrick, The University of Tulsa

METC PROJECT MANAGER: Karl-Heinz Frohne

CONTRACT PERIOD OF PERFORMANCE: July 1, 1985 to May 31, 1987

ABSTRACT

This project is part of the Western Gas Sands Program. The objective of this research is twofold. The first objective is to develop a computational model to represent the hydraulic fracturing geometry and proppant transport for stimulation of lenticular formations in tight western gas sands. The second objective is to apply the computational model to the Multiwell Experiment fracture stimulations. The approach to meeting the first objective is to extend the capabilities of two existing models and combine these models into a single representative model. During the final phase of this three year program, the combined fracture-proppant model will be applied to the Multi-well Experiments in lenticular tight gas sands.

The combined model can handle a contrast of in situ stress that can occur between the pay zone and the bounding zones. The model is also capable of handling all fracture length to height ratios that are greater than one.

The computational model predicts the fracture geometry including variable fracture height, the distribution of proppant during pumping, the buildup of the proppant bed, and the closure behavior after pumping has stopped.

Concerning future activities, this research contract ends in July of 1987, and efforts for extending the model to include foam fracturing and developing a personal computer version of the program are being discussed.

ACCOMPLISHMENTS

- The capability of the fracture geometry model has been extended to include step variations in flow rate and viscosity in the pseudo 3-D model.

- Six particle settling models for non-Newtonian and Newtonian fluid behavior were evaluated and incorporated in the proppant transport model with a user selection option.

- An improved proppant particle tracking system was instituted at the proppant bed-slurry interface to improve the mass balance and fluid volume balance conditions.

- The proppant transport model was extended to represent proppant placement in variable height fracture geometries.

- The semianalytical 3-D fracture model was found to predict results close to values calculated by more sophisticated 3-D models.

- A penny fracture model was developed. The fracture geometry model takes fracture toughness and fluid leak off into account. A two-dimensional flow model was developed for the proppant transport behavior.

- The models have been used to interpret the data of the Multiwell Experiments (MWX). Using a fracture toughness value that increases with fracture length, the predicted pressure and fracture dimensions were found to be in good agreement with the data from the MWX stimulations.

- A simple efficient model to predict fracture geometry and proppant distribution for of lenticular tight gas sand formations has been developed. Programs were sent to METC.

ARTICLES AND PRESENTATIONS

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Palmer, I., and Luiskutty, C.: "Interpretation of MWX Stimulation Results Using Hydraulic Fracture Models," Submitted to J. Geophy. Res.

Sutrick, J., Rybicki, E., Luiskutty, C., and Palmer, I.: "A Computational Model for Proppant Transport in Highly Elongated Hydraulic Fractures of Variable Height," submitted to SPE East. Reg. Mtg. (1987).

Luiskutty, C.: "Modeling Hydraulic Fractures for Various Stress Contrasts Between Pay and Bounding Zones," Proc. AIAA/ASME Symp., Tulsa, Feb. 28, 1987.

Shah, G., Luiskutty, C., and Rybicki, E.: "Sensitivity Analysis of the Semi-analytical 3-Dimensional Model for Hydraulic Fracturing," Proc. AIAA/ASME Symp., Tulsa, Feb. 28, 1987.

Sutrick, J., and Rybicki, E.: "Non-Newtonial Proppant Transport Model," Proc. AIAA/ASME Symp., Tulsa, Feb. 28, 1987.

NOTES

NOTES

SESSION 4B

GAS HYDRATES

Chairman: Rodney D. Malone, METC

OVERVIEW

GAS HYDRATES

by

Rodney D. Malone[1]

In 1983, the U.S. Department of Energy (DOE) assumed the responsibility for expanding the knowledge base and for developing methods to recover gas from hydrates. These are ice-like mixtures of gas and water where gas molecules are trapped within a framework of water molecules. This research is part of the Unconventional Gas Recovery (UGR) Program, a multidisciplinary effort that focuses on developing the technology to produce natural gas from resources that have been classified as unconventional because of their unique geologies and production mechanisms.

Current work on gas hydrates emphasizes geological studies; characterization of the resource; and generic research, including modeling of reservoir conditions, production concepts, and predictive strategies for stimulated wells. Complementing this work is research on in situ detection of hydrates and field tests to verify extraction methods. Thus, current research will provide a comprehensive technology base from which estimates of reserve potential can be made and from which industry can develop recovery strategies.

Gas hydrates research has focused primarily on geology. As work progressed, areas where gas hydrates are likely to occur were identified, and specific high potential areas were targeted for detailed investigation. A Geologic Analysis System (GAS) was developed. GAS contains approximately 30 software packages and can manipulate and correlate several types of geologic and petroleum data into maps, graphics, and reports. The system also contains all well information currently available from the Alaskan North Slope area. Preliminary mapping of hydrate prospects of the Alaskan North Slope is underway.

Laboratory research on gas hydrates includes the characterization of the physical system, which focuses on creating synthetic methane hydrates and developing synthetic hydrate cores using tetrahydrofuran (THF), consolidated rock cores, frost base mixtures, water/ice-base mixtures, and water-base mixtures. Laboratory work produced measurements of the sonic velocity and electrical resistivity of these synthetic hydrates. During 1983, a sample from a natural hydrate core recovered from the Pacific coast of Guatemala was tested for these properties by DOE/METC. More recently, natural hydrate samples acquired from the Gulf of Mexico have been tested.

Modeling and systems analysis work has focused on the development of GAS and preliminary gas hydrate production models. Models were developed for both steam injection and reservoir depressurization methods of gas production from gas hydrates. Concepts for in situ combustion production and for combining the thermal and depressurization concepts were also developed.

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The natural gas hydrate cores will continue to be tested for thermal properties, dissociation properties, fracture mechanics, and optical properties. More sonic velocity and electrical resistivity measurements will be obtained. These activities will include a more detailed study of the Alaskan gas hydrate deposits. Research in the Gulf of Mexico and other target areas has also been initiated. Long-term plans include the determination of diagnostics for hydrate detection, and the development of predictive techniques to forecast production. As this work progresses, field testing and verification activities will be performed. Through the successful completion of these activities, the potential of gas hydrates as a natural gas resource will be assessed, and the technology necessary for the development of the resource will become available.

GEOCHEMICAL AND GEOLOGICAL FACTORS IN THE FORMATION OF GAS HYDRATES

Contract or PTPA Number:	DE-AI2I-83-MC20422
Contractor:	U.S. Geological Survey
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Telephone:	(415) 856-7150
Program Manager (Contractor):	Keith A. Kvenvolden
Principal Investigators:	Keith A. Kvenvolden George E. Claypool
METC Project Manager:	Rodney D. Malone
Period of Performance:	FY 84 - FY 87

ABSTRACT

Availability of methane is the principal limitation on the formation of methane hydrate in deep water marine sediments. A predictive model for marine gas hydrate occurrence requires a quantitative understanding of microbial methanogenesis within the context of marine sedimentation. Critical factors are (1) relative rates of production and preservation of organic matter, and (2) rates and processes of diagenetic degradation of organic matter.

Marine depositional environments have been characterized in terms of pore-fluid chemistry with emphasis on stable isotopic composition of respiratory metabolites. The capacity of the marine sedimentary microbial ecosystem to generate methane has been quantitatively evaluated. Favored sites for abundant methane generation and gas hydrate formation are convergent margin coastal upwelling regions with oxygen-depleted water columns. Pressure effects of accretionary tectonic processes may play a secondary role in making more methane available for gas hydrate formation. Passive margin marine environments also have capacity for development of methane hydrate, but predictability based on measurable geologic and oceanographic factors is not well-developed in the present model. The geologic-geochemical model provides scientifically justifiable estimates of the potential resource base in marine gas hydrates. In addition, the role of gas hydrate formation in the accumulation of conventional natural gas deposits can be better understood.

ALL HYDRATES SAMPLED TO DATE HAVE BIOGENIC METHANE.

ACCOMPLISHMENTS

- Developed geologic-geochemical model of marine gas hydrate occurrence.
- Extended review of world-wide gas hydrate occurrence.
- Documented geological and geochemical conditions at sites where gas hydrates are found.
- Refined methods for estimating the depth of gas hydrate stability in marine sediments.
- Sampled and characterized pore-fluid chemistry of gas hydrate occurrence on the Peru continental margin.

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Kvenvolden, K. A. and Grantz, A. 1988. Decade of North American Geology, (in press).

GEOLOGIC INTERRELATIONS RELATIVE TO GAS HYDRATES WITHIN THE NORTH SLOPE OF ALASKA

CONTRACT NUMBER: DE-AI21-83-MC20422

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METC PROJECT MANAGER: R.D. Malone

PERIOD OF PERFORMANCE: October 1, 1983 to September 30, 1990

ABSTRACT

The USGS North Slope gas hydrate program is divided into two phases. Phase I deals with the evaluation of existing data and the primary goals are to: (1) evaluate geologic controls on gas hydrate occurrences; (2) develop a model for gas hydrate formation; (3) define and evaluate gas hydrate reservoirs; (4) select a coring site for gas hydrate study. Phase II activities are a continuation of Phase I, except the major emphasis is to obtain new data through an active field study program. The field research includes; temperature and borehole gravity surveys, formation water sampling and analysis, detailed geologic/geochemical sampling and analysis of wells, and outcrop studies.

Our model of the physical properties that control gas hydrate stability indicates that hydrates may occur in the Prudhoe Bay area to depths greater then 1,000 m. The construction of a series of cross sections outlining the stratigraphic frame-work has allowed us to evaluate potential fluid and gas migration routes, regional geologic facies relations, and delineate potential gas hydrate reservoirs. Geochemical sampling and well-log analysis show that gas hydrates are often found closely associated with coals. In addition, gas hydrates are reservoired with oil near the Kuparuk River. Future work will emphasize the transition from Phase I of the project into Phase II, with continued geochemical sampling of drilling wells, and the evaluation of identified gas-hydrate bearing reservoirs with temperature and borehole gravity surveys.

ACCOMPLISHMENTS

- Mapped from 136 North Slope well log sets the depth to the base of the ice-bearing permafrost.
- Developed a thermal model within the near-surface (0-2,000m) sediments that includes maps of (1) depth to $0^{o}C$ isotherm, (2) mean-annual surface temperature, (3) temperature at base of ice-bearing permafrost, (4) geothermal gradient within the ice-bearing permafrost, (5) geothermal gradient below ice-bearing permafrost, and (6) ratio between geothermal gradient below the permafrost sequence over the gradient from within the permafrost.
- Evaluated the thermal effect of pore-fluid salinity, pore-pressure variations, and rock grain-size on gas hydrate stability.
- Mapped the depth and thickness of the methane gas hydrate stability field.
- Evaluated geophysical methods for delineating on and off-shore ice-bearing permafrost.
- Completed ten regional geologic cross-sections using 58 wells from western NPRA to the Canning River.
- Completed nine detailed geologic cross-sections using 144 wells from the west end of the Kuparuk River Unit to the east end of the Prudhoe Bay Unit.
- Conducted geologic/geochemical field sampling and analysis of two Kuparuk River Unit drill-sites.
- Tabulated and evaluated geochemical data from seven industry wells in the Kuparuk and Prudhoe Bay units.
- Completed preliminary facies evaluation of the near-surface sediments with the aid of well logs, drill-cuttings, and outcrop field studies.
- Contributed to planning of DOE sponsored First International Conference on Gas hydrate.
- Developed a procedure for conducting a gas hydrate resource estimate.
- Mapped the first approximation of the distribution of the in-situ gas hydrates.

- Conducted and participated in 25 meetings with industry representatives to discuss the gas hydrate program and cooperative work.
- Conducted negotiations with ARCO-ALASKA, CONOCO Inc., and Standard Production to obtain permission to conduct high-resolution temperature and borehole gravity surveys in selected North Slope wells. Permission for surveys pending in the Prudhoe Bay and Kuparuk River units.
- Permission was given by CONOCO to conduct borehole gravity and temperature surveys in six holes from the Milne Point Unit.

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EVALUATION OF GEOLOGICAL RELATIONSHIPS TO GAS HYDRATE FORMATION AND STABILITY

CONTRACT NUMBER: DE-AC21-84MC21181

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METC PROJECT MANAGER: Rodney D. Malone

PERIOD OF PERFORMANCE: October 1, 1984 to September 30, 1987

ABSTRACT

Determination of the relationships of geological environments to gas hydrate formation and stability is the principal objective of the project being conducted by Geoexplorers International, Inc. for the U.S. Department of Energy. The methods of regional basin analysis are applied to assessing the occurrence of and potential gas resources associated with offshore gas hydrates.

Extensive geological studies are carried out for each of 24 locations worldwide with confirmed or inferred evidence of gas hydrates. Sediment composition, provenance, and depositional history in the regions are documented. Structural development of the sedimentary basin in which gas hydrates are indicated is detailed using drilling results and seismic stratigraphic reconstructions. Potential for generation of biogenic methane and conventional thermogenic hydrocarbons is assessed by analysis of existing geochemical data and by thermal modeling.

Evidence for gas hydrates in the study regions is compiled and evaluated in view of the findings of the geological study. All available seismic data, both published and unpublished, are inspected for indications of gas hydrates. Bottom simulating reflectors (BSRs) and other seismic anomalies are mapped. Drilling evidence of possible gas hydrates is reviewed. Instances of possible encounters with gas hydrates by investigators untrained in their recognition are described. Each regional study has a different emphasis dependent on the availability and quality of geologic, geochemical, and geophysical information. Geological and geochemical factors unique to particular regions and those common to many regions are tabulated and used to assess which factors affect gas hydrate formation and stability.

Based on the limited available information, conditional assessments of gas resources are derived. Gaps in the data base of each region are identified. Using measured values or reasonable estimates of sediment properties, quantities of gas contained both in the gas hydrate and possibly trapped beneath the gas hydrate stability zone are estimated.

ACCOMPLISHMENTS

- Completed 11 regional studies of basins encompassing 19 of the gas hydrate locations designated by DOE. Six of the studies have been published by DOE, and are now available to the scientific community. Five studies are in press and will be available soon. Research on the remaining gas hydrate locations is underway.

- Developed the basin analysis approach for study of gas hydrate locations. Published reports examine aspects of regional geology which affect hydrocarbon generation and migration potential. The reports are thus of value not only to gas hydrate researchers, but also as baseline geological studies in exploration for conventional hydrocarbon resources.

- Completed a critical review of gas hydrates in the Russian literature. The study summarizes gas hydrate research by Soviet scientists and evaluated the status of their efforts relative to accomplishments in other countries. The resulting report has been published by DOE and is currently available.

- Identified evidence for gas hydrate presence on many unpublished seismic lines. The vastly expanded data base resulting from our research indicates that gas hydrates are more widespread beneath continental margins than previously documented.

- Discovered evidence of gas hydrate presence in abyssal plain settings.

- Developed computer models of gas hydrate formation conditions incorporating basin-specific values for formation parameters. Conducted computer simulations of the effect of gas hydrate formation on pore water chemistry.

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EVALUATION OF SEISMIC DATA IN THE GULF OF MEXICO

CONTRACT NUMBER: DE-AC21-86MC23145

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METC PROJECT MANAGER: Rodney D. Malone

PERIOD OF PERFORMANCE: August 18, 1986, to August 31, 1987

ABSTRACT

The objective of this project is to evaluate the presence of gas hydrates in the Gulf of Mexico through the collection, interpretation, and analysis of geophysical and geochemical data and to identify pertinent diagnostic criteria for detection of offshore gas hydrates.

Analysis of data for gas hydrate research in the Gulf of Mexico was based on the following procedure:

(1) Low energy seismic data from fathometer, sub bottom profiler and side scan sonar surveys are examined for gas migration indications. The important indicators are mounds (mud volcanos) depressions, faults and gas charged sediments (no record zones). (2) Medium energy seismic data from sparker, boomer and mini-sleeve exploder survey are examined for sea bottom perturbations, faults and gas changed sediments (no record zones), which can be related to low energy seismic indicators. (3) Standard (high energy) seismic survey data are examined for faults, gas charged sediments (no record zones) and anomalous reflectors, which may be related to shallow events recorded on low energy and medium energy surveys. (4) Where there are geochemical data available that may be connected to the low energy seismic surveys, an analysis is made to establish possible relationships. (5) Detailed geologic maps, reports, well logs, and drilling reports of available nearby wells are also examined for anomalies, which may be relevant to gas hydrate research.

The study has concentrated near the Continental slope in the South Marsh Island, East Cameron, West Cameron, High Island, East Breaks, and Garden Banks areas in the Gulf of Mexico. The most promising area includes Blocks 109, 110, 153, and 154 in East Breaks. Sea bottom mounds and conduits where gas has been migrating and/or accumulating can be traced on fathometer, sub bottom profiler, sparker, mini-sleeve exploder, and standard seismic survey data. There are also small "anomalous reflectors" that geophysicists said might be indicative of gas hydrates.

One product of this research project is the procedure of examining all available geophysical data on lease blocks. The low and medium energy data are usually filed and considered for engineering purposes only. Explorationists, who have seen the data retrieved from company archives, are amazed at the detail that can be seen, especially from mini-sleeve exploder and sparker surveys. These data can be stacked and compared directly with standard (high energy) seismic.

THE DEVELOPMENT OF A RESERVOIR SIMULATOR FOR THERMAL RECOVERY OF HEAVY OIL / TAR SANDS IN THE PRESENCE OF HYDRATES

CONTRACT NUMBER: DE-FG-86LC 11075

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METC PROJECT MANAGER: Jim Westhoff

CONTRACT PERIOD OF PERFORMANCE: 9/1/86 - 5/31/87

ABSTRACT

The objective of this project is to analyze the effect of dissociation of gas hydrates during the thermal recovery of heavy oils/tar sands on the North Slope, Alaska. Collett et al. (1984) and Kamath et al. (1987) have reported the presence of gas hydrates in the West Sak and Ugnu sands of Kuparuk River unit. These sands also contain up to 40 billion barrels of heavy crude. Thermal recovery methods such as hot waterflooding, steam flooding and steam stimulation would dissociate these hydrates into gas and water. With the advent of ARCO Alaska, Inc.'s thermal recovery pilot in the West Sak sands, the analysis of effect of dissociation of hydrates on oil recovery has become necessary.

The gas hydrates on the North Slope, Alaska might exist either in the form of layers or distributed throughout the oil bearing formation. The steam or hot water front displacing the oil zone would have different oil recovery efficiencies if a fraction of heat energy is utilized to dissociate the hydrates. The development of a computerized mathematical model (reservoir simulator) for the thermal recovery of heavy oils and tar sands bitumen in the presence of hydrates involves a thermal compositional unsteady state r-z problem with a moving boundary. The unsteady state r-z solution for the moving boundary problem does not exist in the literature and hence the project plan is based upon the systematic development leading towards the final simulator output.

Task plan involves three stages. The first stage considers the layered hydrate/oil configuration. This stage is subdivided into two parts. The first part includes the development of a model to predict the rate of thawing of hydrates as a function of time for a specified heat input rate. The solution of such a problem involves tracking of a moving boundary between the dissociated and hydrate regions in r-z dimension as a function of time. The experience in dealing with the only hydrate situation would be helpful in developing the three- phase-four component unsteady state r-z thermal compositional simulator for the thermal recovery of hydrate-heavy oil configuration.

Task 2 is regarding the development of a r-z simulator for distributed oil/hydrate configuration. Firstly, the heat and mass balance equations are to be developed for the effect of an individual hydrate pocket dissociation on the heat efficiencies. Secondly, the results for the single hydrate pocket will be integrated with the oil zone volume after taking into account the effect of statistical distribution of hydrate pockets.

Task 3 involves the application of the computer models to the West Sak and Ugnu formations. The effect of variables such as porosity, permeability, hydrate zone configuration with reference to the oil zone, thermal conductivity of the hydrate zones, etc. on the cumulative oil production, oil to steam ratios will be evaluated within the limits of the models predictive capabilities.

During the past nine months, we have completed the detailed outline of various tasks involved. The solution of r-z unsteady state moving boundary solution for hydrate dissociation has been already completed. We have also completed the development of equations, discretization, solution procedure, input data selection for the fully implicit thermal-compositional simulator with a moving boundary problem.

ACCOMPLISHMENTS

- Performed a thorough literature search on the development of thermal simulators, gas hydrates in the arctic and characteristics of heavy oils on the North Slope, Alaska.

- Developed a r-z unsteady state thermal model to track the moving boundary between the dissociated and hydrate region under the conditions of constant temperature heat flux in the well bore.

- The complete set of thermal, mass balance, phase behavior relationships was developed to analyze the layered hydrate-heavy oil configuration. This is a three phase, four component unsteady state, non-isothermal r-z simulator with a moving boundary.

- The above set of equations were discretized using a finite difference formulation scheme. The literature search for various possible numerical solutions procedures was completed. A fully implicit numerical procedure with the Newton-Raphson iteration process to account for non-linearities was selected. The derivatives for the Jacobian matrix with respect to the primary variables of temperature, pressure, gas saturation and water saturation were completed. The fortran coding is currently in progress.

- Selected representative property correlations for input data section and included as separate fortran subroutines.

MEASUREMENT AND MODELING OF HYDRATE DISSOCIATION

CONTRACT NUMBER: DE-FG21-86MC23063

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Professor M. Sami Selim

METC PROJECT MANAGER: R. D. Malone

PERIOD OF PERFORMANCE: May 1, 1986 To June 15, 1987

ABSTRACT

The primany objective of this effort is to measure and model mathematically the dissociation of hydrates in sediments at temperatures around the ice point. In order to accomplish the overall above objective, the following four goals must be met:
1. Fabricate artificial methane hydrates in sediments.
2. Measure the thermal conductivity of hydrates in sedmients as a completion of the physical properties necessary for the model.
3. Measure the hydrate dissociatin rate for a confirmation or refinement of the model.
4. Extend our math model review to include Russian models, and to finalize our math model for hydrates in sediment. The fundamental model of hydrates dissociation in sediment will be confirmed and refined by the experimental measurements in objectives 2 and 3 above.

During the first year of this two year project, we have formed methane hydrates successfully in unconsolidated sediments. We have determined that the thermal conductivity instrument, (developed over four years to fulfill the second objective), is one of the best ways to quantify hydrate formation in sediments. While we have been able to form hydrates of miscible hydrate formers (such as tetrahydrofuran and 1,3 dioxolane) in consolidated sediments, we have not been successful in forming methane hydrates in consolidated sediments in our batch system. During the coming year we will form methane hydrate in consolidated sediments using a flow system, initially loaned us by METC.

We have measured the thermal conductivity of hydrates in both consolidated and unconsolidated sediments. We find no effect of hydrate structure or guest molecule on the thermal conductivity of unconsolidated sediments. The thermal

conductivity measurements of miscible hydrate formers in Berea Sandstone (3.5 W/(m-K) at 273 K) will thus represent that of methane hydrate very well.

We have completed the mathematical model of hydrate dissociation in consolidated sediment. With this mathematical model we have performed a sensitivity analysis on hydrate dissociation. Hydrate dissociation is most sensitive to the following parameters: the initial temperature and pressures of the reservoir and the heating medium, the thermal conductivities and thermal diffusivities of both the dissociated and undissociated hydrate zone, and the porosity of the porous media.

ACCOMPLISHMENTS

- Formed hydrates of non-miscible (methane) compounds and miscible compounds (tetrahydrofuran) in unconsolidated sediments in 30 experiments.
- Evaluated three techniques for the quantification of the amount of hydrates formed; calorimetric combustion, pressure drop, and mass loss on dissociation (most accurate)
- Determined a new non-destructive technique - thermal conductivity - as the best (fast and non-destructive) method to quantify hydrate formation in sediments.
- Formed hydrates of tetrahydrofuran and 1,3, dioxolane in consolidated Berea Sandstone sediment.
- Completed a mathematical model for the dissociation of hydrates in consolidated sediments, which incorporates the mass, energy, and momentum conservation transport equations.
- Used the above math model to perform a sensitivity analysis on the physical properties to determine which properties were the most crucial to the success of the model.

ARTICLES AND PRESENTATIONS

Ullerich, J.W., M.S. Selim, and E.D. Sloan "Theory and Measurement of Hydrate Dissociation," presented at the 1986 AIChE Annual Meeting, Miami Beach, November 1986.

Ullerich, J.W., M.S. Selim, and E.D. Sloan, "Theory and Measurement of Hydrate Dissociation," AIChE Journal, 33(5), 747-752 (1987)

GAS HYDRATES THERMOMECHANICS

Contract Number: DE-AC21-84MC21180

Contractor: University of Washington
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Seattle, WA 98195

Contractor Project Manager: Professor Richard C. Corlett

Principal Investigator: Professor Richard C. Corlett

METC Project Manager: Rodney D. Malone

Period of Performance: June 7, 1984 to September 31, 1987

ABSTRACT

The purpose of this project is to experimentally determine the extent to which anisotropic mechanical loading, that is, anisotropic stress state, influences the thermophysical characteristics of gas hyrates. The most important thermophysical characteristics now evident are the pressure P_3 at which decomposition occurs and the rate of decomposition, at a free face not subject to shear when at least one of the principle stresses P_1 and P_2 parallel to that surface exceed P_3; of specific concern are whether P_3 and the rate of decomposition thus measured differ from the corresponding pressure and rate when the mechanical loading is isotropic.

The project is motivated by the fact that most suggested gas hydrates exploitation methods, as well as conventional oil and gas operations in hydrate-bearing formations, inherently impose anisotropic stress states on the medium. No previous investigations of the effect of stress anisotropy on gas hydrate decomposition boundaries and rates have been reported.

The only hydrate studied in this research is methane hydrate. Preliminary experiments showed that pure hydrate samples can be built up by pulse-spraying water droplets on to a surface under methane pressure. Typical conditions are 2 ^{o}C and 70 atm. Hydrate-sand samples can similarly be built up by alternating pulses of water spray and blown sand.

Two basic anisotropic loading configurations have been developed. One achieves end loading P_1 on a methane hydrate cylinder, greater than the gas pressure P_3 applied to the free sides of the cylinder. The other applies radial loading $P_r(=P_1=P_2)$ on the lateral surface of a methane hydrate cylinder greater than the gas pressure P_3 applied to the free end of the cylinder.

In each of the above-described configurations, the gas pressure P_3 is reduced until and beyond the onset of hydrate decomposition.

The onset and rate of decomposition are determined by a differential-thermal method. As the test assembly is gradually depressurized in an isothermal environment a thermocouple in the text section yields a characteristic temperature - time (T-t) curve. By comparison of T-t curves for non-decomposing and decomposing samples, the decomposition heat sink strength as a function of time is revealed.

The equipment and procedures outlined above have been developed and implemented to the point of satisfactory normal function. However, even after over a year of sample formation and experimentation, it has not yet proved possible to achieve consistent sample durability and reproducibility for quantitative data output. This experience suggests that, for future research, a significant investment in experiment automation is desirable and some fundamental research into the hydrates formation process per se is necessary.

ACCOMPLISHMENTS

Original experimental apparatus and procedure, as outlined above, invented and developed.

ARTICLES AND PRESENTATIONS

None.

NOTES

SESSION 5A

WESTERN GAS SANDS

Chairman: Karl-Heinz Frohne, METC

FRACTURING EXPERIMENTS--NEVADA TEST SITE

FTPA NUMBER: DE-AC04-76DP00789

CONTRACTOR: Sandia National Laboratories
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METC PROJECT MANAGER: Karl-Heinz Frohne

PERIOD OF PERFORMANCE: January 1, 1986-June 30, 1987

ABSTRACT

The purpose of the Nevada Test Site Fracturing Experiment is to evaluate fracturing technology for application to unconventional gas recovery. In the past, this has included both hydraulic fracturing and controlled-pulse fracturing. Current experiments were tests of the controlled-pulse technique using a commercial device. Five tests were performed, four of them in open holes for geothermal applications. The fifth test was in a cased hole, perforated with 8 shots per foot in a 90° phased pattern. This test was performed in preparation for a MultiWell Experiment test using Stressfrac as a breakdown tool.

Mineback of both the open and cased hole tests showed maximum fracture lengths on the order of 20 ft. Usually three- to five-ft long fractures propagated from each wellbore in a radial pattern. In the cased hole test, every perforation appeared to be broken down, with separate fractures emanating from each one. The fractures usually coalesced into a nearly single fracture plane within a short distance of the wellbore. Major fractures initiated along each of the perforation planes.

The same tool that was used in the cased hole test (and one open-hole test) was also fielded at the Multiwell Experiment site. However, the MWX test was complicated by our reluctance to use water as a tamp because of the possibility of damaging the natural fracture system. We developed a technique for using liquid carbon dioxide as the tamp fluid and successfully performed the shots. Two 12-ft tools were run separately to cover the full 24-ft zone and measured maximum pressures were 15,600 psi and 12,000 psi. No evaluation of these tests is yet available.

ACCOMPLISHMENTS

- Designed and conducted five controlled-pulse fracturing experiments at the Nevada Test Site. Four of these tests used a commercial propellant tool. One test was in a cased and perforated hole. Maximum fracture lengths of about 20 ft were observed in a radial pattern.

- The cased-hole test used a commercial tool that would be employed at the Multiwell Experiment. During mineback, we found that major fractures initiated from each of the four perforation planes. Measurements of pressure were successfully obtained.

- A controlled-pulse experiment was completed at MWX. The purpose of this test was to break down the perforations in preparation for an interference test. Two Stressfrac shots were conducted successfully under a liquid carbon dioxide tamp to avoid water damage.

ARTICLES AND PRESENTATIONS

Chu, T. Y., Jacobson, R. D., Warpinski, N. R. and Mohaupt, H., "Geothermal Well Stimulated Using High Energy Gas Fracturing," presented at 12th Workshop on Geothermal Reservoir Engineering, Stanford Univ., January 20-22, 1987.

MULTIWELL EXPERIMENT--OVERVIEW

FTPA NUMBER: DE-AC04-76DP00789

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CONTRACTOR PROJECT MANAGER: Dr. David A. Northrop

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Dr. Allan R. Sattler
Dr. Norman R. Warpinski
Dr. Billy J. Thorne
Mr. Paul T. Branagan, CER Corporation

METC PROJECT MANAGER: Karl-Heinz Frohne

PERIOD OF PERFORMANCE: Initiated 10/1/80 and continuing

ABSTRACT

The Multiwell Experiment (MWX) is a research-oriented field laboratory conducted by the U.S. Department of Energy. Its objective is to develop the understanding and technology necessary to allow economic production from one of this nation's unconventional gas resources. This resource is the over 200 trillion cubic feet of natural gas estimated to be within the low permeability, lenticular gas sands in the western United States. The nature of previous field tests has provided insufficient data to unlock this resource. The scope of MWX activities provides a unique research opportunity.

These activities include: (a) closely spaced wells for geologic characterization, interference testing, well-to-well geophysical profiling and downhole fracture diagnostics during stimulation; (b) extensive and comprehensive core and logging programs; (c) measurement of in situ stresses in sandstones and surrounding shales; (d) sedimentological and geophysical techniques to determine reservoir morphologies; (e) seismic diagnostic measurements for hydraulic fracture characterization; (f) pre- and postfrac well testing for reservoir definition and assessment of frac performance; and (g) a series of stimulation experiments.

Three wells (between 115 and 215 ft apart at depth) have been drilled at a site southwest of Rifle, Colorado in the Piceance Basin. Here, the Cretaceous-age Mesaverde--the formation of interest--lies at a depth of 4000 to 8350 ft. Tests have been conducted in the lowermost Corcoran-Cozzette marine sandstones. Stimulation experiment cycles, each consisting of interval characterization, prefrac well tests, stress tests, minifrac and stimulation, and postfrac production tests, have been completed in three different nonmarine intervals.

ACCOMPLISHMENTS

- Established a field laboratory to characterize lenticular, low-permeability

gas reservoirs and to develop the technology to produce them. Six years of tests and stimulations have been conducted in four major intervals.

- Subdivided the 4000 ft Mesaverde Formation by depositional environment into five distinctly different reservoir types: marine, lower (paludal) and upper (coastal) delta plain, meander belt (fluvial) and paralic. The depositional environment controls reservoir morphology, size, internal structure and natural fracturing; thus, it has a profound influence on reservoir performance.

- Demonstrated the significant effect of natural fractures in controlling permeability in tight reservoirs. Have modeled the origin and occurrence of natural fractures in the Mesaverde and defined a novel, unidirectional fracture model.

- Supported the development of tight sands core analysis capability by the service companies. Developed Titegas, an improved log analysis formalism for tight gas reservoirs.

- Developed techniques to quantify in situ stress directions and magnitudes, and used that data in the design and analysis of hydraulic fracture stimulations.

- Showed that the effectiveness of hydraulic fracturing appears limited by an anisotropic natural fracture system, high fracturing pressures, and damage to the fracture system. Thus, alternative techniques, such as directional drilling, will probably be required.

- Proved gas production is strong function of depositional environment and degree of natural fracturing. Breakdowns and extended clean-up times are required for accurate reservoir assessment.

- Developed fully transient, natural fracture reservoir simulator that accurately matches and characterizes well performance.

ARTICLES AND PRESENTATIONS

Over eighty articles have resulted from this project. The most recent include:

Multiwell Experiment Project Groups, Multiwell Experiment Final Report: I The Marine Interval of the Mesaverde Formation, SAND87-0327, April 1987.

Lorenz, J. C., Reservoir Sedimentology of Mesaverde Rocks at the Multiwell Experiment Site and East Central Piceance Creek Basin. SAND87-0040, January 1987.

Branagan, P. T. et al., Case History of Hydraulic Fracture Performance in the Naturally Fractured Paludal Zone: The Transitory Effects of Damage. SPE 16397, SPE/DOE Symposium, Denver, CO, May 1987.

Warpinski, N. R. and Teufel, L. W., In Situ Stresses in Low Permeability, Nonmarine Rocks, SPE 16402, SPE/DOE Symposium, Denver, CO, May 1987.

FTPA NUMBER:	DE-AC04-76DP00789
CONTRACTOR:	Sandia National Laboratories Geotechnology Division 6253 Albuquerque, NM 87185
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PRINCIPAL INVESTIGATOR	Dr. John C. Lorenz
METC PROJECT MANAGER	Karl-Heinz Frohne
PERIOD OF PERFORMANCE:	Initiated 10/1/80 and continuing

ABSTRACT

Two types of geological studies have been conducted at the MWX site: reservoir sedimentology and natural fracture characterization. In the first, reservoir sizes, shapes, and internal heterogeneity (as they affect production of natural gas) have been characterized. Detailed sedimentological study of the Mesaverde Formation at and near the MWX site has allowed the formation to be divided into 5 zones of different depositional environments, each with different types of reservoirs. From the base up, these are:

- Shallow-marine to Shoreline Reservoirs; formed as laterally continuous and relatively homogeneous "blanket" sandstones, interbedded with marine shales.
- Lower Delta Plain (Paludal) Reservoirs; formed as lenticular distributary-channel sandstones (200-500 ft wide) and fan-shaped splay sandstones, interbedded with nonmarine coals and mudstones. They have a fair degree of internal heterogeneity.
- Upper Delta Plain (Coastal) Reservoirs; also formed as lenticular sandstones and splays. The dimensions and degree of internal heterogeneity of these are similar to those of the paludal zone. They are not interbedded with coals, however, and therefore the diagenetic sequence and resulting porosity and permeability are somewhat different.
- Fluvial Reservoirs; formed in sandy meander belts, with dimensions on the order of 1000-2500 ft in width. They are highly heterogeneous, and irregular in shape.
- Paralic Sandstones; formed in nearshore/estuarine environments, and are water-saturated, nonreservoir strata at MWX.

Reservoir rocks at MWX have matrix permeabilities on the order of a few microdarcies or less, and production rates from any of these reservoir types are dependent on (and controlled by) the system of natural fractures present in the reservoirs. The fractures enhance effective reservoir permeablities to a few millidarcies. Geologic study of the fractures has focused on their character, properties, and origin. These studies have shown that:

- The fractures are low stress, regional fractures, the distribution of which within the reservoirs is controlled by reservoir heterogeneity, and therefore by the depositional environment.
- For many of the MWX reservoirs, a single, subparallel, unidirectional fracture set is present, creating highly anisotropic horizontal permeabilities.
- Although most of the fractures are mineralized by quartz and/or calcite, fracture-parallel permeability (measured in the laboratory) is still significantly greater than matrix permeability.
- In a few MWX reservoirs (notably the Cozzette), a secondary fracture set may be present, which helps interconnect the regional fractures, and greatly enhances total reservoir permeability.
- Fracture spacing in these reservoirs is highly irregular, and is significantly less than reservoir thickness. However, less than 10% of the fractures extend the full height of the reservoir, and the concept of "fracture spacing" is not applicable to these rocks.

ACCOMPLISHMENTS

- Subdivided the Mesaverde Formation by depositional environment and reservoir type.
- Characterized each reservoir type: size, shape, internal characteristics.
- Characterized Mesaverde fracture systems and their control on the production of natural gas.
- Defined/characterized a new, unidirectional, subparallel, "regional" fracture system and its effects on reservoir permeability.
- Summarized the tectonic history of the basin and the probable origin of the regional fracture system.
- Demonstrated that important fractures systems can occur in reservoirs that are not located on structure.

ARTICLES AND PRESENTATIONS

More than a dozen articles are available from the principal investigator.

FTPA NUMBER: DE-AC04-76DP00789

CONTRACTOR: Sandia National Laboratories
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Mr. Craig Cipolla, CER Corporation

METC PROJECT MANAGER Karl-Heinz Frohne

PERIOD OF PERFORMANCE: Initiated 10/1/80 and continuing

ABSTRACT

The primary purposes of the MWX fracturing experiments are to (1) test the applicability of current technology for the stimulation of Western tight gas sands, (2) determine where improvements of current technology are needed and (3) develop new technology where current practices are inadequate. We perform relatively small, highly instrumented hydraulic fracture experiments in well characterized zones in order to determine hydraulic fractures parameters as well as any deleterious effects on the reservoir. Characterization includes detailed reservoir and rock properties from core (usually in at least two of the three wells), determination of lens geometry and orientation from well and outcrop data, detailed stress testing in and around the stimulation interval, three-well interference tests to determine reservoir behavior, core studies of natural fractures to determine orientation and production characteristics, studies of the fluid fracturing system for damage and leakoff characteristics, and other studies of rock and fluid interactions. Instrumentation includes bottomhole pressure and temperature during the treatments, surface measurements of all flow rates (gas, liquid, slurry), densities, pumped volumes, temperatures and pressures as well as all recovered volumes. Diagnostics such as temperature and gamma surveys, borehole geophones in the offset wells, and others are usually included. Analysis of the data integrates geometry results from the diagnostics and history matching of the pressure data using a pseudo-3D fracture model. Results are compared with postfrac interference well tests to yield our best interpretation of the stimulation results.

During the last eighteen months we have concentrated on the fluvial interval, in particular the "B" and "C" sands. A full scale stimulation experiment was conducted in the B sand which showed that leakoff increased by a factor of about 50 above a threshhold pressure. This resulted in extreme loss of fluid and rapid screenout when treatment pressures surpassed this threshhold. Two

minifracs were subsequently conducted in the C sand to determine if this was a common feature in the fluvial zone, to further quantify the leakoff characteristics, and to determine if we could shut off the leakoff with appropriate additives. These tests have proved relatively successful.

ACCOMPLISHMENTS

- Completed fracture experiments in the paludal and coastal intervals in previous years.

- Completed the fracture experiment in the B sand. This included detailed characterization, in situ stress measurements, laboratory tests, pre- and postfrac interference tests, a minifrac and a propped stimulation, and diagnostics. The major finding was the occurrence of accelerated leakoff above a threshhold pressure which results in a rapid screenout condition.

- Determined the stress distribution in sands and mudstones in the lower fluvial section. We found that mudstones in this interval do not have as high stress as in other intervals and fracture containment is not as good.

- Completed two minifracs in the C sand to verify the accelerated leakoff finding. We observed the same phenomenon and found that 100 mesh sand would reduce the leakoff. However, we also found that height growth is more of a problem in this zone.

- During the C sand minifracs, we measured the stress changes in one of the offset wells due to the treatment. We found that the stress change is significant and we should be able to alter the stress field so that hydraulic fractures can be forced to propagate in the orthogonal direction and cross more natural fractures.

ARTICLES AND PRESENTATIONS

Warpinski, N. R., Branagan, P. T., and Wilmer, R., "In Situ Stress Measurements at U.S. DOE's Multiwell Experiment Site, Mesaverde Group, Rifle, Colorado," JPT, Vol 37, pp 527-536, March, 1985.

Warpinski, N. R., Branagan, P. T., Sattler, A. R., Lorenz, J. C., Northrop, D. A., Mann, R. L. and Frohne, K-H, "Fracturing and Testing Case Study of Paludal, Tight, Lenticular Gas Sands," SPE Formation Evaluation, Vol. 2, June, 1988.

Warpinski, N. R. and Teufel, L. W., "In Situ Stresses in Low-Permeability, Nonmarine Rocks," SPE 16402 Proceedings, 1987 SPE/DOE Joint Symposium on Low Permeability Reservoirs, pp 125-138, Denver CO, May, 1987.

MULTI-WELL EXPERIMENT -- FRACTURE DIAGNOSTICS

CONTRACT NUMBER: DE AC04-76DP00789

CONTRACTOR: Sandia National Laboratories
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Albuquerque, New Mexico 87185

CONTRACTOR PROJECT MANAGER: Dr. Paul J. Hommert

PRINCIPAL INVESTIGATORS: Dr. Billy Thorne
Mr. Harry Morris

METC PROJECT MANAGER: Karl-Heinz Frohne

PERIOD OF PERFORMANCE: Initiated 10/1/80 and continuing

ABSTRACT

The primary objective of this project is to develop diagnostics for remotely mapping hydraulic fractures. Current activities are focusing on fracture mapping using a Borehole Seismic System (BSS) that detects microseisms associated with the fracture. During the past year, redesign of the hardware, software, and data reduction techniques associated with a triaxial Borehole Seismic System have made possible better estimates of hydraulic fracture geometry. The redesigned triaxial system now incorporates three geophones per axis and provides 30 times the downhole gain of the replaced system, resulting in improved signal-to-noise ratios. This stronger signal, together with an increased digitization rate for each of the six simultaneously digitized channels from two borehole seismic tools, has made possible the acquisition and processing of data that were previously inaccessible. The new electronics make use of a null system and an improved calibration system which includes a synthetic event generator to produce sinusoidal signals of specified amplitude, frequency, and phase. These make readjustments to maintain system balance possible while the tool is in place downhole. A maximum likelihood event location scheme, which incorporates a newly developed algorithm based on the use of directional statistics, is used to compute the location of microseisms and error estimates for these locations. The accuracy of the redesigned system, based on the ability to locate perforation shots, indicates a 25 ft (7.6 m) uncertainty in the location of individual microseisms. This results in a fairly high level of confidence in the determination of the azimuth of the November 1, 1986, hydraulic fracture in the fluvial zone at DOE's Multiwell Experiment Site.

In addition to the application of the BSS for fracture mapping, further examination of the data from perforation shots indicates the potential of the

BSS to be used with an active source to determine natural fracture orientation. This is true because the perforation data are consistent with an anisotropic velocity field, presumably as a result of natural fractures, at the Multiwell Experiment Site.

ACCOMPLISHMENTS

* Completed an upgrade of the borehole system that included 30 times the downhole gain, improving signal to noise ratios. The digitization rates have also been increased to provide more easily analyzable data sets.

* Utilized two tools simultaneously to map the November 1, 1986, hydraulic fracture in the fluvial zone. The fracture azimuth determined from the data was consistent with the azimuth that would be expected from independent information.

* Utilizing a single tool, mapped the mini-frac conducted in May, 1987.

* Analyzed the perforation data to demonstrate that velocity anisotropies present in the data are consistent with the alignment of the natural fracture system. This result indicates the potential of the BSS to determine natural fracture orientation.

* Incorporated into the tool the ability to independently excite the vertical and horizontal geophones so that potential tool resonance problems could be examined.

MWX RESERVOIR TESTING

CONTRACT NUMBER: Sandia Contract No. 01-6852, Amendment No. 1

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Mr. Craig Cipolla

METC PROJECT MANAGER: Mr. Karl-Heinz Frohne

PERIOD OF PERFORMANCE: January 1, 1986 to December 31, 1986

ABSTRACT

During the 1986 calender period the CER efforts in reservoir engineering, field activities and analysis in support of the MWX project focussed on the following two primary objectives:

- Reentry well testing of the previously stimulated Paludal and Coastal intervals in an attempt to assess the time dependence of stimulation/ fracture damage mechanisms on production; and
- To test, evaluate, stimulate and analyze the first large Fluvial sandstone lens, the Fluvial B.

These objectives were accomplished first by integrating a variety of geologic, geotechnical, and reservoir testing data into both analytic and numeric reservoir models. These model results provided a most probable scenario for both the unstimulated and stimulated reservoir and formed the basis for planning and executing field activities and subsequently shaping our final conclusions concerning the effectiveness of the various tests and experiments. The field testing programs were scheduled, formulated and executed after numerous discussions with METC, Sandia project personnel and formal consultation with the MWX industry panel of advisors. This research methodology was effectively utilized in the reentry testing of the Paludal 3 and 4 sandstones, where the decision to perform the test was based upon modeling and other interpretative data that suggested removal of residual stimulation liquids, presumably through imbibition, should permit increased production over previous post-stimulation tests and thus be more indicative of the real enhancement produced by the propped fracture.

The largest and most prolific gas reservoirs in the Mesaverde lie within the Fluvial interval and thus being of primary interest to the MWX project. The Fluvial B was chosen as the first of the Fluvial lenses for comprehensive testing and analysis. The 3 MWX wells were initially used during pre-frac interference and tracer testing, later as part of a seismic experiment during a

variety of stimulation techniques and finally during interference test of the post-stimulation evaluation. Test data and analysis have permitted a very reasonable and probable assessment to be made of reservoir production and the effects resulting from the stimulation experiments.

Future activities include an altered stress experiment in the Fluvial interval and the incorporation of new impulse loading gaseous perforation breakdown techniques in an effort to eliminate any liquid contact with the natural fracture system. The largest Fluvial lens, the Fluvial E, is scheduled to be the subject of the next set of MWX experimental activities.

ACCOMPLISHMENTS

- Single well reentry test of the previously stimulated Paludal 3 and 4 sandstones following an 18 month isolation period in an effort to determine the long term effects of stimulation reservoir damage;
- Single well reentry test of the previously stimulated Coastal Yellow sandstone following a 6 month isolation period in an effort to determine the long term effects of stimulation reservoir damage;
- Interference pressure and stress monitoring in observation wells during gaseous nitrogen and other perforation breakdown techniques in the Fluvial B;
- Three well interference pre frac well tests of the Fluvial B;
- An Argon tracer test using the 3 MWX wells in the Fluvial B;
- Nitrogen fracturing and KCl water breakdown along with interference pressure measurements; and
- A Post Mini frac and Stimulation 3 well interference well test.

A number of significant findings and conclusions concerning reservoir engineering in very tight naturally fractured reservoirs have been furnished as the result of the experiments conducted at MWX. In particular, the salient conclusions center on describing the productive nature and characterization of the natural fractures that appear so pervasive in the very tight matrix sandstones found at MWX. This information has been transmitted to the industry in general through SPE papers and has been met with considerable interest and concern.

ARTICLES AND PRESENTATIONS

Branagan, P. et al: Case History of Hydraulic Fracture Performance in the Naturally Fractured Paludal Zone: The Transitory Effects of Damage, SPE/DOE paper 16397 presented at the SPE/DOE Joint Symposium of Low Permeability Reservoirs, Denver, May 18-19, 1987.

Branagan, P. et al: Comprehensive Well Testing and Modeling of Pre- and Post-Fracture Performance of the MWX Lenticular Tight Gas Sands, SPE/DOE paper 13867 presented at the SPE/DOE Joint Symposium of Low Permeability Reservoirs, Denver, May 19-22, 1985.

Warpinski, N.R et al: Fracturing and Testing Case Study of the Paludal Tight Lenticular Gas Sands, SPE/DOE paper 13876 presented at the SPE/DOE Joint Symposium of Low Permeability Reservoirs, Denver, May 19-22, 1985.

NOTES

SESSION 5B

ARCTIC/OFFSHORE RESEARCH

Chairman: Harold D. Shoemaker, METC

OVERVIEW

ARCTIC AND OFFSHORE RESEARCH

by

Harold D. Shoemaker[1]

The DOE Arctic and Offshore Research (AOR) Program emphasizes the development of an Arctic energy-related technology information system and the advancement of new knowledge in sea ice and seafloor/soils research to advance the technology needed to economically recover the fossil resources of the Alaska Arctic. These AOR activities include (1) development of an Arctic energy-related technology information system, (2) determination of ice island generation off the Arctic ocean ice shelves and their drift paths into the Alaskan Beaufort Sea, (3) measurement and analysis of seafloor seismic activity, (4) seasonal changes in temperature and salinity at the seabed and how they influence seabed freezing and the occurrence of permafrost, (5) assessment of the problems in the utilization of the other Arctic fossil resources, and (6) determination of the feasibility of recovering oil and gas resources in deep ice-covered waters. The AOR program is four years old. The base line development of the AOR information system is nearing completion. It contains listings on 86 Arctic data bases, over 7,000 bibliographic citations, and sea ice and seafloor quantitative data from the bibliographic citations. The ice island study is approximately 65 percent complete. Salinity profiles (basically fresh water) and the weather patterns and conditions that favor major ice island movement have been determined to characterize and model ice island movement. The seafloor seismic project is about 75 percent complete. A seafloor seismic unit has successfully monitored two July 1986 earthquakes near offshore platforms in southern California. The seafloor freezing study (nearing completion) has successfully collected one years data on water column salinity and temperatures at the seafloor. The assessment of the problems in utilizing the other Arctic fossil resources and the subice energy recovery feasibility studies are in the planning stages.

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ICE ISLAND CHARACTERIZATION

CONTRACT NUMBER: DE-AC21-83MC20037

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PRINCIPAL INVESTIGATORS: Dr. W.M. Sackinger
Dr. M.O. Jeffries

METC PROJECT MANAGER: H.L. Shoemaker

PERIOD OF PERFORMANCE: Sept. 30, 1983 - Sept. 30, 1987

ABSTRACT:

The forces exerted against offshore oil production structures by moving, drifting ice islands, which are up to 190 feet thick and 19 miles in length, are extreme and may limit the cost and recoverability of oil in Arctic offshore locations. The thrust of this program is to estimate the probability of interaction between ice islands and structures by gathering and analyzing data on their generation, size, trajectories, life and other properties. A cluster of some 26 ice islands, created in 1982 by calving from the Ward Hunt Ice Shelf, has been instrumented with satellite-telemetered data stations, and the relationship between the winds, currents, and ice island trajectories has been examined in considerable detail. The historical statistics of ice island generation have been compiled, and a statistical model for Arctic winds is being formulated to simulate the ice island trajectories as they pass through the Alaskan oil production area.

ACCOMPLISHMENTS:

- Examined and compiled historical records on ice island production for 4 decades;
- Discovered weather conditions conducive to ice island production;
- Documented 26 recently-produced and eight old ice islands;
- Studied ice shelf growth and replenishment to help estimate ice island creation over the next 4 decades;
- Trajectories of 6 ice islands have been recorded for over 1 year, along with local weather conditions causing the motion;
- Relationships between winds and ice island trajectories have been established for large movement events;

- Effects of pack ice restoring forces on the edge of moving ice islands have been quantified;
- A model for ice island movement has been developed and verified.

ARTICLES AND PRESENTATIONS:

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JEFFRIES, M.O. (in press). The growth, structure and disintegration of Arctic ice shelves: a review. Polar Record, 1987.

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SACKINGER, W.M., SERSON, H.V., JEFFRIES, M.O., SHOEMAKER, H.D. and YAN, M. (1985). Ice island generation and trajectories north of Ellesmere Island, Canada. Proceedings of the Eighth International Conference on Port and Ocean Engineering under Arctic Conditions (POAC 85), Narssarssuaq, Greenland, 7-14 September 1985, 1009-1040.

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SACKINGER, W.M. and YAN, M. (1985). Generation and movement of ice islands near the Canadian Arctic Archipelago. In, Proceedings of Arctic Oceanography Workshop, Bay St. Louis, Missouri.

SACKINGER, W.M. (1984). Ice island generation and trajectories. In, Proceedings of the Arctic Energy Technologies Workshop, November 1984, Morgantown, W. Va.

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JEFFRIES, M.O. and KROUSE, H.R. Floating ice dams and their effects on fiord oceanography and fiord ice growth, northern Ellesmere Island, Canada. Journal of Geophysical Research.

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SEAFLOOR EARTHQUAKE MEASUREMENT SYSTEM

CONTRACT NUMBER: DE AC04-76DP00789

CONTRACTOR: Sandia National Laboratories
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METC PROJECT MANAGER: Harold Shoemaker

PERIOD OF PERFORMANCE: October 1, 1977 - September 30, 1986

ABSTRACT

A significant consideration in the design of offshore structures for seismically-active regions is their response to earthquakes. An appropriate design methodology would involve the synthesis of wave propagation/structural vibration models with in-situ soil/structural response models. The reliable use of soil response models requires that they be validated by comparison with seafloor sediment response data during an earthquake event. While there is considerable data available on land-based soil response during an earthquake, very little data has been obtained for seafloor sediment response. With the overall objective of providing validated seafloor response models, Sandia National Laboratories has designed, fabricated and deployed a Seafloor Earthquake Measurement System (SEMS). The most recent of these systems was deployed in the Beta Field near two Shell Oil Company platforms, offshore Long Beach, California. During July 1986, two significant earthquakes were recorded by the SEMS unit. The data from these events have been filtered and compared against land-based measurements of the same earthquakes. The data indicate that relative to the land-based measurements, the vertical amplitudes of acceleration are significantly reduced on the seafloor. These results, which were consistent with data obtained in 1981, may have implications for platform design.

The current program objectives include the implementation of simplified attenuation models so that the land-based and seafloor data can be compared and the mechanisms associated with the reduced vertical acceleration can be investigated. In addition, work has been initiated to consider the siting, design, fabrication, and deployment of a second SEMS unit, also offshore California. This unit will permit an enlargement of the current data base and will incorporate modest design improvements over the unit currently active off of Long Beach.

ACCOMPLISHMENTS

* Using the SEMS technology, successfully recorded and retrieved, by remote interrogation, the seafloor response to two earthquakes. The response was recorded in the near vicinity of two oil platforms that were instrumented to measure platform response to an earthquake.

* Analyzed the data and determined that in comparison with land-based measurements, the seafloor response showed significantly reduced vertical acceleration amplitudes.

* Continued to monitor the current SEMS unit with quarterly interrogations.

* Initiated an effort to fabricate another SEMS unit for deployment offshore California.

SPRAY ICE BONDING TO OFFSHORE STRUCTURE COATINGS

CONTRACT NUMBER: DE-AC21-83MC20037

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PERIOD OF PERFORMANCE: Sept. 30, 1983 - Sept. 30, 1987

ABSTRACT:

The sudden onset of high winds due to polar lows in the ice edge regions of the Bering, Chukchi, and Beaufort Seas produces spray ice accretion on petroleum production structures, offshore loading equipment, and service vessels. In a search for a reliable, passive method of minimizing spray ice accretion, a study has been completed of the shear strength of the bond between spray ice and a variety of candidate coatings which could be applied to structures.

ACCOMPLISHMENTS:

- Naturally-formed sea spray ice was collected and characterized;
- Four categories of spray ice were defined;
- The broad range of spray ice salinity, density, and crystal size was determined;
- A new method for measuring shear strength of the bond of spray ice with a substrate was developed;
- Bond strengths were measured for several surfaces and coatings, and two favorable coatings were found.

ARTICLES AND PRESENTATIONS:

SACKINGER, W.M., NORDLUND, O.-P., GRUOL, V., ROWLES, S., GROVES, J. and FEYK, C. (1986). Development of quantitative information on Arctic sea ice and ice island movement, thickness and mechanical properties: adhesion and physical properties of naturally formed spray ice. In, Proceedings of the Gas Hydrates, Arctic/Offshore Research and Deep Source Gas Contractors Review Meeting, C.A. Komar (ed.). US Department of Energy, Morgantown Energy Technology Center, Morgantown, W. Va., DOE/METC-86/6037, 81-89.

SACKINGER, W.M., NORDLUND, O.-P., and SHOEMAKER, H.D. (1986). Low adhesion coatings for sea spray ice on offshore drilling units in northern waters. In, PolarTech '86, International Offshore and Navigation Conference and Exhibition, Helsinki, Finland, 27-30 October 1986, 512-527.

SACKINGER, W.M., SHOEMAKER, H.D. AND FEYK, C. (1986). Spray ice formation, characteristics and adhesion to ship and structure coatings. In, Proceedings of the Third Annual Arctic Offshore Technology, Conference (AOTC), Calgary, Alberta, 28-31 October 1986.

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Abstract

The principal objectives of this effort are (1) develop an on-line directory that identifies and describes other data bases containing Arctic energy-related information and how to access them, (2) develop a bibliographic/management information system containing references and abstracts on Arctic energy-related research, (3) develop a scientific and engineering technology information system containing quantitative data on sea ice and seafloor/soils characteristics, and (4) make the AORIS available via computer to the user community on a realtime basis.

The AORIS has an on-line thesaurus and user-friendly aids to assist in querying the AORIS. There are three principal components: a directory that lists 85 other data bases containing Arctic energy-related information and how to access them; a bibliography/management information system (B/MIS) containing approximately 7,000 references and abstracts on energy-related research; and a scientific and engineering information system (SEIS) containing quantitative data on sea ice, ice gouging/scouring, and subsea permafrost characteristics from the B/MIS citations. The AORIS also contains grey literature, i.e., data and/or locations of Artic data collected but never published.

Results/Accomplishments

Roadmap -- The roadmap or directory component of the AORIS contains a listing of 86 data bases containing Arctic topics of interest to those interested in developing Arctic offshore oil and gas. The B/MIS and SEIS components of the AORIS gave priority to Arctic engineering and geotechnical information and data. The roadmap complements the B/MIS and SEIS by guiding the user to sources of Arctic information in these and the major Arctic topic areas. When a particular data base is called up, besides the title, the other information displayed includes data base type, subject matter, data base developer or producer, whether there are on-services or not, whether access through a gateway, whether it is open to the public, whether hard copies or reports are available, long time span of literature contained in the data base, how often the data base is

updated, who to contact including telephone number and address, and a summary abstract describing the contents of the data base or library center.

B/MIS -- The bibliograhic/management information system (designated BIBLIO on screen in AORIS) currently contains over 7,000 Arctic energy-related citations. The B/MIS component of the AORIS provides searches of articles, journals, books, and other publications dealing with Arctic topics as sea ice, ice gouging or scouring, seafloor/soils, subsea permafrost, seismic activity, pipelines, offshore structures, icebreakers, and subice hydrocarbon development technology. The B/MIS is structured as a user friendly, menu-driven information system to expedite the search procedure, and to enable the user to use the AORIS with as little instruction as possible. Scientific and nonscientific personnel alike have searched the AORIS with ease and without documented helps. The initial or baseline B/MIS has been completed and uploaded on a DOE/METC VAX 11/780 computer (November 1986).

SEIS -- The scientific and engineering information system (designated DATA on screen in AORIS) is currently in the development phase. It will contain quantitative data on sea ice, ice gouging or scouring, and subsea permafrost characteristics in both tabular and graphical formats. The initial prototype SEIS will be operational in early Fall 1987.

The sea ice data section will concentrate on identifying data on ice distribution, movement, morphology, and mechanical and physical properties in U.S. waters (Beaufort, Chukchi, and Bering Seas). It will present abstracted information to the user in several formats. In cases where the original report contained the results of a statistical analysis, the information will be available as an author statistics file which provides a tabulated summary of these statistics. A histogram plot will be displayed where grouped frequency data have been abstracted. Text files will be used to present excerpts from those reports which provide qualitative descriptions of results and observations. When movement data are retrieved, track maps will display the drift patterns. If the original data from a project are available in raw form, i.e., magnetic tapes, a pointer will be provided to indicate its location.

The ice gouging/scouring data section hierarchy categorizes the data by area; date; gouge type; and gouge characteristics, distributions, and effects. The gouging section will also concentrate on gouge statistics, such as spatial distribution, frequency of recurrence, and data used to generate statistical results.

The subsea permafrost data section will contain data necessary for characterizing permafrost in particular offshore areas. These will be categorized by geographic location, consisting of subdivisions of the Beaufort, Chukchi, and Bering Seas, and other offshore areas in the U.S. Arctic which are in the permafrost zone; and by date, when the research was performed. Generic data for the various soil types and permafrost depths will also be available. These may be input to predictive thaw models. The subsea permafrost data will be organized into three general data categories: distribution characteristics, and properties.

NOTES

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UNCONVENTIONAL GAS RECOVERY

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