PROJECT NARRATIVE

Solicitation Number: DE-PS26-04NT42072
Subtopic Area: 1-Understanding Tight Gas Resources

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Title of Project:

Analysis of Critical Permeability, Capillary and Electrical Properties for Mesaverde Tight Gas Sandstones from Western U.S. Basins

Date: 03/30/05

ABSTRACT

Tight gas sandstones (TGS) represent 72% (342 Tcf) of the projected unconventional resource (474 Tcf) for the United States. Rocky Mountain tight gas sandstones representing 70% of the total TGS resource base (241 Tcf; USEIA, 2004) and Mesaverde Group tight gas sandstones represent a principal gas productive unit in Western U.S. basins including the basins that are the focus of this project (Washakie, Uinta, Piceance, Upper Greater Green River, Wind River). Industry assessment of the regional gas resource, projection of future gas supply, and exploration programs require an understanding of the reservoir properties and accurate tools for formation evaluation of drilled wells. The goal of this project is to provide petrophysical formation evaluation tools related to relative permeability, capillary pressure, electrical properties and algorithm tools for wireline log analysis. Detailed and accurate moveable gas-in-place resource assessment is most critical in these marginal gas plays and there is need for quantitative tools for definition of limits on gas producibility due to technology and rock physics and for defining water saturation.

Tasks involved with meeting the project objectives include clarification and review of the research plan (Task 1), initial technology assessment (Task 2), collection and consolidation of published advanced rock properties data into a publicly accessible relational digital database and collection of at least 300 rock samples and digital wireline logs from 4-5 wells each from five basins that will represent the range of lithofacies present in the Mesaverde Group in these basins (Task 3). Basic properties (including routine and *in situ* porosity, permeability, and grain density) of these rocks will be measured and, based on these properties, 150 samples will be selected to represent the range of porosity, permeability, and lithofacies in the wells and basins (Task 4.1). Measurements to be performed on these selected samples comprise: 1) Drainage critical gas saturation (4.2), Routine and in situ mercury intrusion capillary pressure analysis (4.3), cementation and saturation exponents and cation exchange capacity using multi-salinity method (4.4), geologic properties including core description, thin-section microscopy, including diagenetic and point-count analysis (4.5), and standard wireline log analysis (4.6). The compiled published data and data measured in the study will be input to an Oracle database (5.1). XML code will be written that will provide web-based access to the data and will allow construction of rock catalog format output sheets based on user-input search and comparison criteria. The data will also be available as a complete Oracle database (5.2). Core and wireline log calculated properties will be compared and algorithms developed for improved calculation of reservoir properties from log response (Task 6). To evaluate the scale dependence of critical gas saturation bedform-scale reservoir simulation models will be constructed that represent the basic bedform architectures present in the Mesaverde sandstones. Simulations will be performed that will parametrically analyze how critical gas saturation and relative permeability scale with size and bedding architecture (Task 7). An active web-based, publication, and short-course technology transfer program will be performed (Task 8).

This project represents a two-year collaboration of the Kansas Geological Survey at University of Kansas and The Discovery Group, Inc. The projects requests $411,030 of US Department of Energy funds over two years to support the program and technology transfer activities. The project manager is Alan P. Byrnes with the KGS (phone: 785-864-2177; email: abyrnes@kgs.ku.edu.

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List of Acronyms

AAPG – American Association of Petroleum Geologists
CEC – Cation Exchange Capacity
KGS – Kansas Geological Survey
KU – University of Kansas
KUCR – University of Kansas Center for Research, Inc.
KUERC – University of Kansas Energy Research Center
md – millidarcy
NETL – National Energy Technology Laboratory
PPTD – Principal pore throat diameter
PTTC – Petroleum Technology Transfer Council
Sgc – critical gas saturation
SOPO – Statement of Project Objectives
SPE – Society of Petroleum Engineers
Tcf – trillion cubic feet
TGS - tight gas sandstone(s)
USDOE – United States Department of Energy
USEIA – United States Energy Information Administration
XML – eXensible Mark-up Language

Analysis of Critical Permeability, Capillary and Electrical Properties for Mesaverde Tight Gas Sandstones from Western U.S. Basins

1. SCIENTIFIC AND TECHNICAL MERIT

1.1 Knowledge of State-of-Art

1.1.1 Statement of Problem – Tight gas sandstones (TGS) represent 72% (342 Trillion cubic feet, Tcf) of the projected unconventional gas resource (474 Tcf). Rocky Mountain TGS are 70% of the total TGS resource base (241 Tcf; USEIA, 2004) and the Mesaverde Group represents the principal gas productive sandstone unit in the largest Western U.S. TGS basins. Industry assessment of the regional gas resource, projection of future gas supply from this region, and exploration programs require an understanding of the reservoir properties and, when wells are drilled, accurate tools for formation evaluation. The proposed project addresses fundamental questions concerning: 1) gas flow, 2) capillary pressure, 3) electrical properties, 4) facies and upscaling issues, 5) wireline log interpretation algorithms, and 6) providing a web-accessible database of advanced rock properties. 1) ***Gas Flow***- All assessments of gas resource are premised on assumptions concerning gas relative permeability and implicitly, the critical gas saturation (Sgc) or minimum gas saturation at which gas flows. Some assessments assume that if gas is present its' recovery is only a matter of price and/or technology. This premise is not valid for gas saturations less than critical. Limited research has been done in this area and published data can be interpreted to indicate that Sgc increases with decreasing permeability. This would eliminate some gas from being produced and from resource base estimates. Understanding the minimum gas saturation necessary for gas flow (Sgc) is fundamental to defining the tight gas sandstone resource and is particularly critical to quantify in marginal resources. 2) ***Capillary***

Pressure - While there is a good understanding of the influence of confining stress on permeability and porosity in tight gas sandstones, little work has been done for capillary pressure. 3) ***Electrical Properties*** - Extensive work has been done defining regional water composition, but there is little published work characterizing the effect of cation exchange (Waxman-Smits effect) on modifying standard Archie-calculated water saturations from wireline log response for Mesaverde rocks. 4) ***Facies and Upscaling*** - Beyond investigating the above fundamental properties for representative lithofacies in the Mesaverde, the proposed project will investigate how critical gas saturation, capillary pressure, electrical properties, upscaling issues, and wireline log response and analysis change with Mesaverde rock properties such as lithofacies, porosity, and permeability and how flow properties upscale with lithofacies bedding architecture. 5) ***Data access*** **–** The body of data concerning TGS advanced rock properties is extensive but few companies have been able to devote the time or resources to compiling the data and make the data digitally accessible. A well-designed internet-accessible database is needed to both provide access to the library of data, query the data with respect to user-defined relational issues, and provide a framework for future data input through XML linkage.

1.1.2 Background and Existing Technologies/Methodologies - The US DOE has supported research concerning tight gas sandstone properties for over three decades and it can be conservatively assessed that much of the major work in this area has been directly related to this funded effort. The extensive nature of this work is one of the reasons that there is a need to compile the quantitative data into a single, easily accessible, petrophysical database. Comprehensive background review of the state of the art in TGS core petrophysics is prohibitive for this proposal but brief reference to important work and work performed by team members of the present proposed project helps to clarify research needs and how the proposed project will provide an improvement on existing technology. Discussion of work on the topics directly addressed by the proposed program is briefly preceded by discussion of the more fundamental properties of porosity and permeability.

1.1.2.1. Porosity - Extensive work has been performed on the stress dependence of porosity and permeability of TGS and the laboratory conditions necessary for proper basic properties measurements on low-permeability sandstones are now widely recognized. For porosity Walsh and Grosenbaugh (1979) developed a model for fracture compressibility that matches low-permeability data well and can be expressed by a linear porosity change with logarithmic change in stress. Ostensen (1983) illustrated for low-permeability rock data from Jones and Owens (1980) and Sampath (1983) that these data conformed to the model of compressing cracks. Byrnes (1997, 2000, 2003) illustrated a relationship between routine and *in situ* porosity for Mesaverde/Frontier and Medina/Tuscarora tight gas sandstones. Once cores are under *insitu* confining stress, low-permeability rocks exhibit pore-volume compressibilities consistent with their high degree of consolidation and crack closure, between 1×10^{-6} and 7×10^{-6}/psi (Jones and Owens, 1981; Byrnes, 1997; Castle and Byrnes, 1998; Luffel, 1991).

1.1.2.2. Permeability – Extensive previous work on low-permeability sandstones has shown that the difference between permeabilities measured at routine conditions and those measured at confining stress increases progressively with decreasing permeability and increasing confining stress. Byrnes et al (2001) and Byrnes (2003) presented a relationship between *in situ* Klinkenberg gas permeability (k_i) and routine air permeability (k_{air}): $\log k_{ik} = 0.059 (\log k_{air})^3 - 0.187 (\log k_{air})^2 + 1.154 \log k_{air} - 0.159$; where k is in millidarcies. The trend is due both to the increase in effect of confining stress on pore-throat size with decreasing permeability and to the increase in gas slippage (i.e., Klinkenberg effect) with decreasing pore-throat size and decreasing permeability (Vairogs et al, 1971; Thomas and Ward, 1972; Byrnes et al, 1979; Jones and Owens, 1980; Sampath and Keighin, 1981; Walls et al, 1982; Ostensen, 1983; Wei et al, 1986; Luffel et al, 1991; Byrnes, 1997; Castle and Byrnes, 1998; Byrnes et al, 2001).

Given that the dominant control on permeability is pore throat size and pore size distribution, differences in permeability-porosity (k-ϕ) relations between different lithofacies reflect changes in the relationship of how mechanical and chemical compaction influenced total porosity and how they affected pore throats. Mesaverde-Frontier sandstones can be characterized as exhibiting either a log-linear k-ϕ relationship (Byrnes 1997) or, for subpopulations may exhibit a power-law trend (Castle and Byrnes,1998; Byrnes and Castle, 2000; Webb et al, 2005). It is interesting to note that low-permeability sandstones for basins across the U.S. exhibit similarity in the nature of the of k-ϕ slope with change in the intercept as a function of the degree of diagenesis , lithofacies, grain size and other lithologic variables (Figure 1).

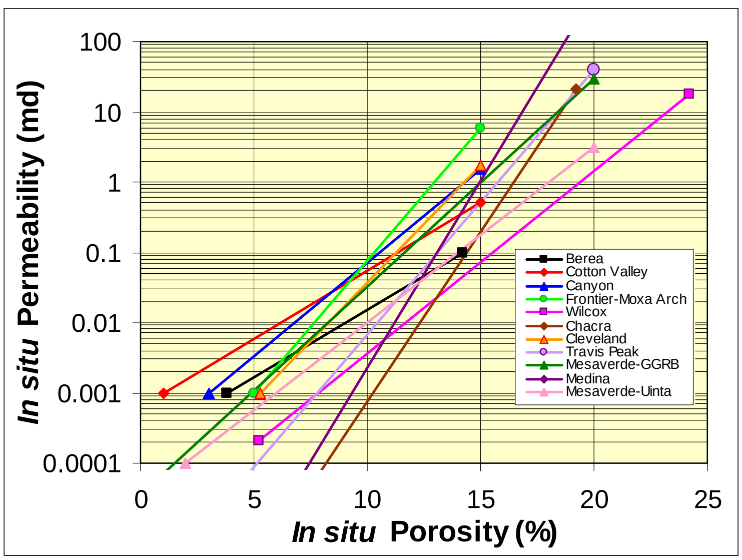


Figure 1. Permeability vs. porosity for low-permeability sandstones from various formations. The log-linear k-ϕ relationship can be modeled using: $\log k_i = 0.32 \pm 0.10\ \phi_i - 5.05 \pm 1.48$ where the variance in the slope and intercept reflects variance of equations terms between formations. Data from various sources including Dutton et al, 1993; Byrnes, 2003; Castle and Byrnes, 2005)

1.1.2.3. Relative Permeability and Critical Gas Saturation - Relative gas permeability data, representing k_{rg} values obtained at a single S_w, and complete k_{rg} curves with k_{rg} values obtained for single samples at several saturations have been reported in several studies (Thomas and Ward, 1972; Byrnes et al, 1979; Jones and Owens, 1981; Sampath and Keighin, 1981; Walls, 1981; Ward and Morrow, 1987; Byrnes, 1997; Castle and Byrnes, 1997; Byrnes and Castle, 2001). Byrnes et al (1979) utilized a modified Corey (1954) equation to predict gas relative permeability in low-permeability sandstones:

$$k_{rg} = (1 - (S_w - S_{wc,g})/(1 - S_{gc} - S_{wc,g}))^p \, (1 - ((S_w - S_{wc,g})/(1 - S_{wc,g}))^q)$$

where S_w is fractional water saturation, S_{gc} is the fractional critical gas saturation, $S_{wc,g}$ is the fractional critical water saturation relevant to the gas phase, and p and q are exponents expressing pore size distribution influence. Compiling published low-permeability data, Byrnes (2003) showed that low-permeability gas sandstone relative permeability could be modeled using the following terms (Figure 2):

$S_{wc,g} = 0.16 + 0.053*\log k_{ik}$ (where if $k_{ik} < 0.001$ md then $S_{wc,g} = 0$)

$S_{gc} = 0.15 - 0.05*\log k_{ik}$; p = 1.7; q = 2

where $S_{wc,g}$ and S_{gc} are expressed in fractions and k_{ik} is expressed in md.

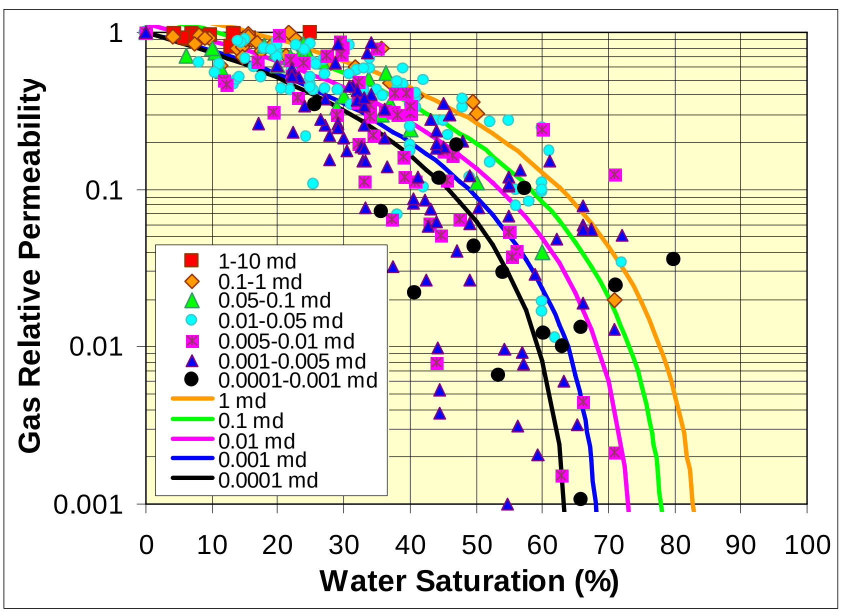


Figure 2. Gas relative permeabilities measured at single water saturations shown parametrically with sample k_{ik}. Curves show Corey predicted $k_{rg,Sw}$ values for samples with k_{ik}=0.0001 md to k_{ik}=1 md using Equations in text. Note abrupt decrease in kr at Sw >50% and how Sgc appears to increase with decreasing permeability (after Byrnes, 2003).

A consequence of Figure 2 is that either: 1) the kr exponent, p, is constant (p=1.7) and critical gas saturation, Sgc, increases with decreasing absolute permeability, as expressed in the equations presented above, or 2) Sgc is approximately constant at some low value (5-15%) and the Corey exponent, p, changes with decreasing permeability. To date, this question has not been addressed in publication.

1.1.2.4. Capillary Pressure - Because of small pore-throat size, low-permeability gas-producing sandstones are typically characterized by high water saturation and high capillary pressure (Thomas and Ward, 1972; Dutton et al., 1993; Byrnes, 1997). Relationships between "irreducible" water saturation and permeability (Byrnes, 1997; Byrnes and Castle, 2000) and between threshold entry pressure and principal pore throat diameter (PPTD) and permeability (Byrnes and Keighin, 1993; Keighin, 1995; Byrnes, 1997; Byrnes, 2003) have been published. The relationship between threshold entry pressure or PPTD and permeability and between permeability and lithofacies at any given porosity requires that capillary pressure change with lithofacies at any given porosity. With change in both the threshold entry pressure and pore throat size distribution with decreasing permeability, Byrnes (2003) illustrated generalized capillary pressure shapes for western tight gas sandstones (Figure 3). Byrnes and Keighin (1993) and Keighin (1995) showed that the *in situ* PPTD values range from 15-84% of unconfined PPTD values illustrating the change in capillary pressure with confining stress. Though work has been done on capillary pressure of low-permeability sandstones little work has been published on the lithofacies or pressure-dependence of capillary pressure.

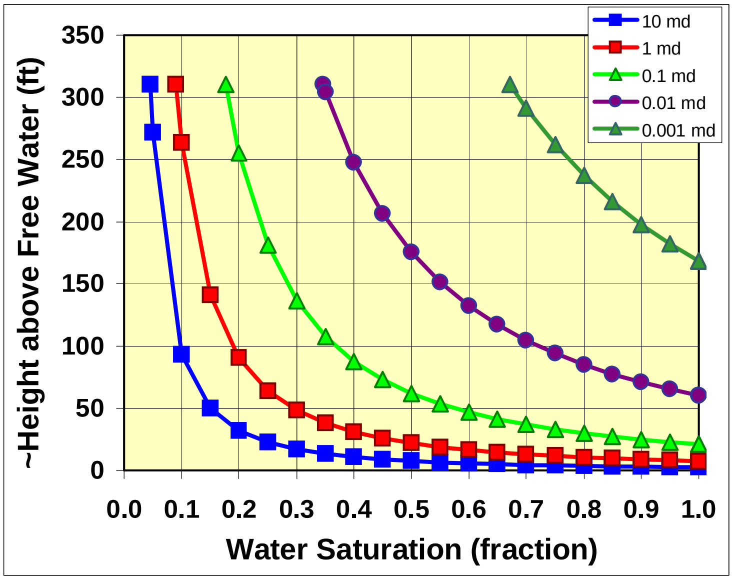


Figure 3- Generalized capillary pressure curves expressed as approximate height above free water level for Mesaverde/ Frontier for different permeabilities. Entry pressure increases with decreasing k_{ik} and S_{wi} becomes more difficult to define as k_{ik} decreases because Pc curves are still in transition zone despite high gas column heights. Curves shown for higher permeability rocks are for clean sandstones. Sandstones with more diagenetic clay exhibit greater "irreducible" water saturations.

1.1.2.5. Water Saturation and Cation Exchange Capacity – Wireline log determination of water saturation and identification of pay in tight gas sandstones is complicated by the low porosity, argillaceousness, and, in some rocks, the high cation exchange capacity (CEC) of the clays in the sandstones. The problems of wireline log analysis in shaly sands is well recognized (Fertl, 1987; Worthington, 1985) and numerous algorithms have been proposed for calculating water saturations in shaly sands including the empirical Simandoux (1963) and Fertl equations, which correct for the apparent formation resistivity by a factor related to a shale volume estimate, and the more theoretical Dual Water and Waxman-Smits (Waxman and Smits, 1969; Waxman and Thomas, 1974; Clavier, Coats, and Dumanoir, 1984) methods, which are based on theoretical considerations of clay conductance and electrical current flow in a rock comprised of non-conductive matrix, conductive clays, fluid filled pores, and bound water on clay surfaces. In rocks containing clay in contact with fresher water, resistivity can be suppressed due to the electrical current carrying capacity of cations exchanged with the clay surfaces. The extent of suppression is a function of water salinity, the cation exchange capacity of the clay, the volume and surface area of the clay, and the specific counter-ion activity. To account for these effects Waxman and Smits (1969) redefined the Archie equation.

To calculate water saturation, accurate values of formation factor, saturation exponent, and cation exchange capacity (if present) are needed. Further, the accuracy and importance of water saturations should be investigated before decisions on completion intervals and reserve estimates are made. The DOE has supported a study by Advanced Resources International to catalogue water composition data for the Greater Green River and Wind River basins. While these data are critical to log-calculated water saturation, significant saturation error can exist if CEC effects are present and are not accounted for in water saturation calculations. Isolated CEC data are available for Mesaverde but no comprehensive study has been published. The effects may prove small or may be able to be effectively handled by empirical log analysis methods but validation of a method is required.

1.1.2.6. Scale Dependence of Sgc and Relative Permeability - Even if accurate relative permeability curves are known it is important to understand how to utilize them in reservoir modeling and simulation and have an understanding of how properties can and can't be accurately upscaled. Analytically rigorous solutions for upscaling of permeability and relative permeability exist only for the simplest architectural geometries such as layered beds (e.g., Weber, 1982; Craft and Hawkins, 1991; Corey and Rathjens, 1956) or for specific permeability architectures (Kortekaas, 1985; Honarpour et al., 1995; Ringrose et al., 1996). Other than averaging, alternate viable methods for upscaling to create larger-scale pseudo-functions involve such methodologies as: renormalization to progressively increase the homogenization scale (King, 1989) and the use of the MHD equation based on homogenized transport equations and stochastic properties (Lenormand, 1997). The most accurate, but most computationally intensive, method for calculation of pseudo-functions is to use flow simulations performed for representative architectures (Warren and Price, 1961; Desbarats, 1987). A goal of the proposed project is examine this issue by creating theoretical common tight gas sandstone bedding architectures, populated by the measured relative permeabilities to determine how architectures affect predicted performance under various upscaled systems that are more representative of field-scale performance.

1.2 Scientific and Technical Discussion

1.2.1 Technology/Methodology Proposed **–** The project proposes to address the issues discussed above by compiling and collecting public data and newly measured data. The tasks involved and the analyses to be performed are discussed briefly here and in more depth in Section 2.1 of Technical Approach and the SOPO (Appendix A). The compilation and digitization of published advanced rock properties data (Task 3) will utilize the library resources and library support at the KGS and KU and off-the-shelf Oracle database software. XML code and program code for providing a user-friendly interface for database query and data analysis (Task 5) will utilize off-the-shelf JAVA and other software.

It is proposed to measure basic properties (2.1), critical gas saturation (2.2) , routine and *in situ* mercury capillary pressure (2.3), Archie and cation exchange capacity electrical properties (2.4) , and geologic properties (2.5) on a select population of approximately 25 Mesaverde Group cores obtained from widely spaced wells in five Western U.S. basins. From the cores from the 25 wells 300 core plugs will be obtained that appropriately represent the complete range of lithofacies exhibited by the Mesaverde in each of the basins. Sampling is designed to obtain a complete spectrum and not just reservoir facies. From the 300 core plugs a select population of

150 core plugs will be selected that will adequately represent the range of lithofacies, porosity, and permeability in the Mesaverde. While a larger population is obviously desirable measuring advanced properties on a larger sample set is prohibitive. By quantitatively measuring the geologic properties of the core plugs the study provides a defined geologic (lithofacies, petrologic) reference frame for correlation with rocks from unsampled Mesaverde areas and other formations. Similarly, obtaining data on a nearly complete spectrum of Mesaverde rocks significantly increases the robustness of the empirical relationships developed and provides users of the database with a high probability of finding analog samples. Laboratory analyses will employ established methodologies.

The above approach utilizes existing methods and a formation evaluation approach that has been used in a number of multi-company commercial studies performed by the principal investigators of this proposal. While commercial rock catalogs, where companies submit samples of interest and share petrophysical results, are useful, the absence of a full population and, particularly, poorer reservoir quality samples, precludes the ability to define properties for significant fractions of the rock lithofacies/property spectrum. The experimental design of the proposed study deals directly with this issue.

The project will analyze wireline log response, evaluate results, and determine log-analysis algorithms that provide apparent maximum accuracy (Task 6). The analysis approach will utilize standard statistical methods but will closely integrate log-core-petrophysical data.

While core-plug scale Sgc values represent a minimum Sgc, heterogeneities introduced by complex bedforms and architectures of different lithofacies can increase Sgc at larger scales. Reservoir simulation models will be constructed to represent basic bedform architectures. These models of common bedform architectures in the Mesaverde will be used to explore and better define how petrophysical properties upscale (Task 7). For example, this analysis will examine how Sgc increases with increasing bedform complexity.

Finally, a basic goal of the project is to provide the data compiled and measured to operators and users involved in resource evaluation (Task 8). An active web-based, publication, and short-course technology transfer program will be performed. The web-based tools will provide any operator with complete access to the database and a tool for querying and analyzing data. Publications will explore important relationships in the nature and distribution of properties and the relationships between properties.

1.2.2 Relationship to Solicitation Goals - The proposed project directly addresses the issues discussed above concerning s improving characterization of multiphase flow, relative permeability, and capillary pressure in tight reservoirs and data management. These issues were properly identified in the solicitation as three of the four areas in which advances are sought. The project will create a database of selected relative permeability, capillary pressure, and electrical properties for Mesaverde Group tight gas sandstones (TGS) from five Western U.S. basins and will answer fundamental questions discussed in Section 1.1.1. Answers to these questions, and subsidiary questions concerning the relationships between variables, are fundamental to definition of reservoir relative permeability, capillary pressure and water saturation. On a larger scale, the accurate definition of these properties is necessary to provide improved ability to assess and predict formation producibility of Mesaverde tight gas reservoir targets in Western U.S. basins. Although recent assessments of marginal, sub-economic resources indicate that hundreds to thousands of trillion cubic feet (Tcf) of gas exists in-place in tight gas reservoirs, the full and accurate appraisal of TGS potential is founded on an understanding of rock properties.

The compilation of published and newly measured data into a web-accessible database, organized in a user-definable rock catalog format where relational structures between data can be explored “on-the-fly”, will provide significant accessibility to the data at any personal computer. Additionally, for companies interested in incorporating the data into their internal proprietary databases, the availability of the entire Oracle database itself will be possible and will facilitate input and immediate use.

1.3. Expected Project Impacts and Benefits

***1.3.1 Impact* –** It is believed the properties measured and the database will have an immediate and significant impact on quantitative resource assessment of Mesaverde and other tight gas sandstones. Depending on the nature of critical gas saturation change with lithofacies and permeability, the recoverable gas resource and exploration programs in Western tight gas sandstones could change significantly. Waxman-Smits parameters for Mesaverde rocks could provide operators with tools that may indicate water saturations are 10-20% less than values calculated using standard Archie parameters. This difference could immediately change completion, stimulation, and modeling practices. The availability of a database of advanced properties compiled from the literature and the study will provide immediate evaluation tools.

***1.3.2 Applicability* –** The project is designed to provide data that is applicable to Mesaverde reservoirs and to similar facies in other formations. The measurement of properties on a suite of rocks that represent the range of lithofacies, porosity, and permeability in the Mesaverde is specifically designed to provide the maximum applicability of the results obtained. The construction of a web-accessible database will provide a tool that facilitates use of the data immediately. All operators in tight gas sandstones will have use for the data and the database.

1.3.3 Risks **–** The experimental methodologies employed in the proposed program are well established. There are no significant risks to the program. The project is designed to sample approximately 25 wells to obtain the representative sample of cores. It is possible that the wells selected will not provide sufficient variance in the lithofacies or porosity/permeability population. If this occurs additional wells will be sampled or alternate wells will be selected. Unlike many published studies where rock geologic properties are not quantified, since these will be characterized in this study, there will be quantitative data for users to determine the similarity of their particular rocks to those in the database.

2.0 TECHNICAL APPROACH

2.1 Statement of Project Objectives

ANALYSIS OF CRITICAL PERMEABILITY, CAPILLARY AND ELECTRICAL PROPERTIES FOR MESAVERDE TIGHT GAS SANDSTONES FROM WESTERN U.S. BASINS

A. Objectives

Major aspects of the proposed study involve a series of tasks to measure data to reveal the nature of drainage critical gas saturation, capillary pressure, electrical properties and how these change with basic properties, such as porosity and permeability, and lithofacies for tight gas sandstones of the Mesaverde Group, and possibly between basins. A goal of the project is to measure critical gas saturation (Sgc) and capillary pressure (Pc), using 150 rocks selected to represent the range of lithofacies, porosity and permeability in the Mesaverde in five major TGS basins (Washakie, Uinta, Piceance, Upper Greater Green River, and Wind River). Representative samples will be obtained from 4-5 wells in each basin and the advanced properties samples selected form a set of not less than 300 samples to obtain the distribution of properties needed. This investigation will discern the relative relationship between the independent geologic and petrophysical variables and Sgc and Pc. In Mesaverde reservoirs diagenetic clays with high cation exchange capacity can be common and water salinities can often be fresh (<25,000 ppm total dissolved solids). These conditions can lead to low resistivity for which the standard Archie analysis of wireline electric log response must be modified (e.g. Waxman-Smits, Dual Water approaches). An objective of the project is to evaluate this for the select samples to both determine the nature of conductive solids and develop algorithms for wireline log analysis of water saturation. A principal goal is to compile published data and newly measured data into an Oracle database that is publicly available and which will be fully accessible on the web allowing search and development of relational structures of the data and output both as structured data and in user-defined rock catalog format.

B. Scope of Work

Tasks involved to meet the project objectives are described in the Statement of Project Objectives (SOPO, Appendix A) and includes clarification and review of the research plan (Task 1), initial technology assessment (Task 2), collection and consolidation of published advanced rock properties data into a publicly accessible relational digital database and collection of at least 300 rock samples and digital wireline logs from 4-5 wells each from five basins that will represent the range of lithofacies present in the Mesaverde Group in these basins (Task 3). Basic properties (including routine and *in situ* porosity, permeability, and grain density) of these rocks will be measured and, based on these properties, 150 samples will be selected to represent the range of porosity, permeability, and lithofacies in the wells and basins (Task 4.1). Sampling will not focus on just reservoir quality samples. The creation of a population of core samples that represents the complete range of properties exhibited by the Mesaverde is important to defining rock properties. Measurements to be performed on these selected samples comprise: 1) Drainage critical gas saturation (4.2), Routine and *in situ* mercury intrusion capillary pressure analysis (4.3), cementation and saturation exponents and cation exchange capacity using multi-salinity method (4.4), geologic properties including core description, thin-section microscopy, including diagenetic and point-count analysis (4.5), and standard wireline log analysis (4.6). The compiled published data and data measured in the study will be input to an Oracle database (5.1). XML code will be written that will provide web-based access to the data and will allow construction of rock catalog format output sheets based on user-input search and comparison criteria. The data will also be available as a complete Oracle database for companies wishing to load the data into their own systems (5.2). Core and wireline log calculated properties will be compared and algorithms developed for improved calculation of reservoir properties from log response (Task 6). To evaluate the scale dependence of critical gas saturation bedform-scale reservoir simulation models will be constructed that represent the basic bedform architectures present in the Mesaverde sandstones. Simulations will be performed that will parametrically analyze how critical gas saturation and relative permeability scale with size and bedding architecture (Task 7). An active and aggressive web-based, publication, and short-course technology transfer program will be performed (Task 8).

C. Tasks To Be Performed

Task 1. Research Management Plan

A draft and DOE-approved final Research Management Plan will be constructed comprising a detailed work breakdown structure, summary of objectives and tasks, schedules, expenditures by task.

Task 2. Technology Status Assessment

A comprehensive draft and DOE-approved final review of the information and technology relevant to the proposed work will be performed and an analytical summary report prepared. This task will precede and compliment the activities under Task 3.

Task 3. Acquire Data and Materials

Subtask 3.1. Compile published advanced properties data – The DOE and industry have supported research into TGS petrophysical properties for over 30 years. Advanced rock properties data, comprising compressibility, effects of confining pressure, capillary pressure, relative permeability, and electrical properties, will be compiled from published studies and DOE reports. These data will be digitized and entered into a fully integrated digital data system accessible to external users. The databases will also be designed to use many of the capabilities of the existing DOE-supported, web-based, public-domain software, GEMINI (Geo-Engineering Modeling through INternet Informatics, Contract No. DE-FC26-00BC15310). GEMINI provides small independent operators with web-based tools for petroleum database access, data mining, and geological and engineering analyses.

Subtask 3.2. Compile representative lithofacies core and logs from major basins - Not less than 300 rock samples will be obtained from 4-5 wells in each of the five basins in the project (Washakie, Uinta, Piceance, Upper Greater Green River, Wind River). The 4-5 wells in each basin will be selected to provide a wide geographic distribution and will be limited to wells that have adequate wireline log suites and core. In each of the basins possible industry sponsors have been identified. For areas that need to be sampled but industry contribution cannot be obtained wells will be selected that have core available in the USGS core repository in Denver, Colorado. Cores and wells will be selected that provide a comprehensive range in lithofacies, both reservoir and nonreservoir, characteristic of the Mesaverde in the area and basin and that serve both the objectives of the study and assessment needs of the industry participants.

Subtask 3.3. Acquire logs from sample wells and digitize – For each of the wells from core is obtained, the complete suite of available wireline logs will be obtained. As note, only wells where an adequate suite of wireline logs is available will be selected for sampling. For wells where logs are not available digitally paper copies will be digitized by a commercial service company.

Task 4. Measure Rock Properties

Subtask 4.1. Measure basic properties (k, ϕ, grain density) and select advanced population – Routine core analysis will be performed on not less than 300 core samples. Data to be obtained include: whole-core porosity, permeability and grain density where previously measured; routine helium porosity, routine air and *in situ* Klinkenberg permeability, and grain density. These measurements are intended to provide a basis for selecting the representative 150 samples for more advanced testing.

Subtask 4.2. Measure critical gas saturation – Critical gas saturation will be measured on not less than 150 samples. Cores will be not less than 2-inches long and gas pressures will be incrementally increased until breakthrough is achieved. Saturations will be determined gravimetrically. Critical non-wetting phase (gas equivalent) saturation will also be measured during the *in situ* mercury intrusion capillary pressure analysis on not less than 150 samples. For mercury intrusion analysis significant change in electrical conductivity across the sample provides a clear indication of breakthrough.

Subtask 4.3. Measure in situ and routine capillary pressure – Capillary pressure analysis will be performed on not less than 150 pairs of representative samples. Mercury intrusion analysis from 2 to 10,000 psi injection pressure will be used. Paired samples, exhibiting similar porosity, permeability, and lithology will be used for the unconfined analysis and the confined analysis.

Subtask 4.4. Measure electrical properties – Electrical resistivity analysis will be performed on 150 samples. Cores will be sequentially vacuum/pressure saturated with brines of three different salinities. Once a plug has reached equilibration with the brine it will be placed in a Hassler-type core holder and subjected to in situ hydrostatic confining stress. Electrical resistivity will be measured using a two-electrode configuration with gold plated end electrodes. Waxman-Smit effects will be determined from the change in resistivity with change in brine conductivity. Following cementation exponent measurements the core will be desaturated by gas displacement as described under Subtask 2.2.

Subtask 4.5. Measure geologic and petrologic properties – Cores will be described to provide an understanding of pay and nonpay rock types, their log signatures, lithofacies, stratigraphy, depositional sequences, and flow-unit continuity. The cores will be graphically logged with emphasis on lithology, including bedform type argillaceousness, small-scale (i.e., centimeters to meter-scale) heterogeneities, porosity type and distribution, and macro-scale diagenetic products. Based on the lithofacies present, 300 representative samples will be selected for basic core analysis. On the 150 samples selected for advanced properties analysis, Thin-section point count analysis (300 counts) will be performed to assist in characterization of rock composition and rock and pore architecture. Petrography will also evaluate size, volume, geometry, and evolution of pore systems. Core photos and thin-section photomicrographs will illustrate observations and interpretations.

Subtask 4.6. Perform standard logs analysis – Log petrophysical analysis will be performed to the determine porosity, log signature, Archie –calculated water saturation, and calculated permeability for every interval where a core sample is obtained. This analysis will provide the basis for identifying unique wireline log signatures for lithofacies. This will also act as the basis for evaluating the need to develop better analysis algorithms to improve prediction of petrophysical properties from log response.

Task 5. Build Database and Web-based Rock Catalog

Subtask 5.1. Compile published and measured data into Oracle database – All data, including the compiled previously published data and data measured in the proposed project, will be compiled and input into an Oracle database including petrophysical data (core and log) and rock images.

Subtask 5.2. Modify existing web-based software to provide GUI data access –The existing KGS web-based software for petrophysical database query and analysis (DOE-supported, web-based, public-domain software, GEMINI (Geo-Engineering Modeling through INternet Informatics, Contract No. DE-FC26-00BC15310) provides small independent operators with web-based tools for petroleum database access and mining, and geological and engineering analysis to delineate resources and increase exploitation efficiency. Source code modules from GEMINI will be utilized to create stand-alone software for access and utilization of the TGS database, including download, storage, and parsing of data, and on-the-fly relational data compilation and report generation. The interface will be designed to be user-friendly, utilizing a graphical-user-interface, and allow, via user-selected options, the creation of rock catalog page(s) that address the query structure defined by the user to address their needs. Rather than present a "flat" rock catalog this will provide the ability for users to construct their own rock catalog pages presenting the data they need to see in a relational context relevant to the problem they are addressing. Rock catalog pages will be able to display output such as user-selected tables, cross-plots (e.g. k vs. ϕ, k vs. $P_{confining}$, etc.), core and thin-section images, and wireline log response. Submodules will be added to the Rock Catalog Module to retrieve and display advanced rock properties including capillary pressure, relative permeability, waterflood susceptibility, rock mechanics, and electrical properties. Overlays will be constructed and added to the existing Rock Catalog Panel to select and access data sets and select plot display options. Code will be written to provide conversion of advanced properties between different parameters, such as transformation of capillary pressure to hydrocarbon height above free water level. Output can to be added to Rock Catalog reports.

Task 6. Analyze Wireline-log Signature and Analysis Algorithms

Subtask 6.1. Compare log and core properties – Wireline log-calculated properties, including porosity, water saturation and lithofacies, will be integrated and compared with core-derived properties including porosity, permeability, lithofacies and capillary pressure-derived water saturation. Possible unique log signatures for lithofacies will be evaluated and differences between standard log-calculated parameters and core properties will be analyzed.

Subtask 6.2. Evaluate results and determine log-analysis algorithm inputs – Based on the comparison of log and core properties in Subtask 4.1 analysis will be performed to try an develop algorithms that can improve wireline log-predicted properties. Linear, nonlinear and neural network approaches will be investigated and compared. For water saturation calculations analysis will be made of the Archie, Waxman-Smits, Dual-water, and Simandoux methods.

Task 7. Simulate Scale-dependence of Relative Permeability

Subtask 7.1. Construct basic bedform architecture simulation models – While core-plug scale Sgc values represent a minimum Sgc, heterogeneities introduced by complex bedforms and architectures of different lithofacies can increase Sgc at larger scales. Reservoir simulation models will be constructed to represent basic bedform architectures. These models will only explore common bedform architectures in the Mesaverde and will not be comprehensive.

Subtask 7.2. Perform numerical simulation of flow for basic bedform architectures – Reservoir simulation will be performed for the simulation models constructed in Subtask 5.1. Modeling will explore parametrically the influence of porosity, permeability, gas saturation, and relative permeability differences assigned to the basic lithofacies architectural elements in the models.

Task 8. Technology Transfer, Reporting, and Project Management

Subtask 8.1 Technology Transfer - An active web-based, publication, and short-course technology transfer program will be performed. The web-based tools will provide any operator with complete access to the database and a tool for querying and analyzing data. Publications will explore important relationships in the nature and distribution of properties and the relationships between properties.

Subtask 8.2. Reporting Requirements - All reporting requirements of the DOE, federal agencies, and other governmental entities will be fulfilled in a timely manner.

Subtask 8.3. Project Management - Alan Byrnes will manage the project with members of the team shown in the Management and Key Personnel Section 4.0.

D. DELIVERABLES

Periodic, topical, and final reports will be submitted in accordance with the "Federal Assistance Reporting Checklist". A list of deliverables by task includes:

Task 1.0 – Draft and DOE-approved final Research Management Plan
Task 2.0 - Draft and DOE-approved final review of the information and technology relevant to the proposed work
Task 3.1- Bibliography of advanced rock properties TGS papers
Task 3.2- Core plugs (not less than 300) from representative lithofacies from five major basins and corresponding wireline logs
Task 4.1- Basic properties data for core plugs compiled in Task 1.2
Task 4.2- Critical gas saturation measurements on representative samples (150 samples)
Task 4.3- *In situ* and routine mercury capillary pressure on representative samples (150 samples)
Task 4.4- Archie cementation and saturation exponents and salinity independent m* & n* from multiple salinity measurements (150 samples)
Task 4.5- Core description and core photos, thin section point-count analysis, scanning electron microscope on selected samples (150 samples)
Task 4.6- Digital wireline log data for core intervals
Task 5.1- Oracle database of published and measured rock properties
Task 5.2- Web-based software tool for constructing rock catalog pages, searching database, analyzing database
Task 6.1- Comparison and analysis of standard wireline-log response interpreted properties and core properties
Task 6.2- Development of algorithms for wireline-log interpretation
Task 7.1- Reservoir simulation models of basic bedform architectures relevant to sandstones analyzed at various scales
Task 7.2 - Numerical reservoir simulation of models to evaluate scale dependence of advanced properties
Task 8.1- publicly available Oracle database
Task 8.2 - Web-accessible database of advanced properties and GUI tool for access and analysis of data
Task 8.3- Workshop on rock properties
Task 8.4- Presentation of results to petroleum industry through various publications

E. BRIEFING/TECHNICAL PRESENTATIONS

The KGS and Discovery Group will prepare detailed briefings for an annual presentation to DOE, explaining plans, progress, and results of the technical effort. The KGS and Discovery Group will provide and present a technical paper(s) at the DOE Annual Contractor’s Review Meeting. Workshops, seminars, and presentations through the North Midcontinent PTTC and other appropriate channels (e.g., AAPG and local organizations) will be conducted.

2.2 Labor Hours and Categories

Table 1 shows allocation of manpower by task for project personnel. Labor estimates for laboratory activities are based on appropriate effort/sample.

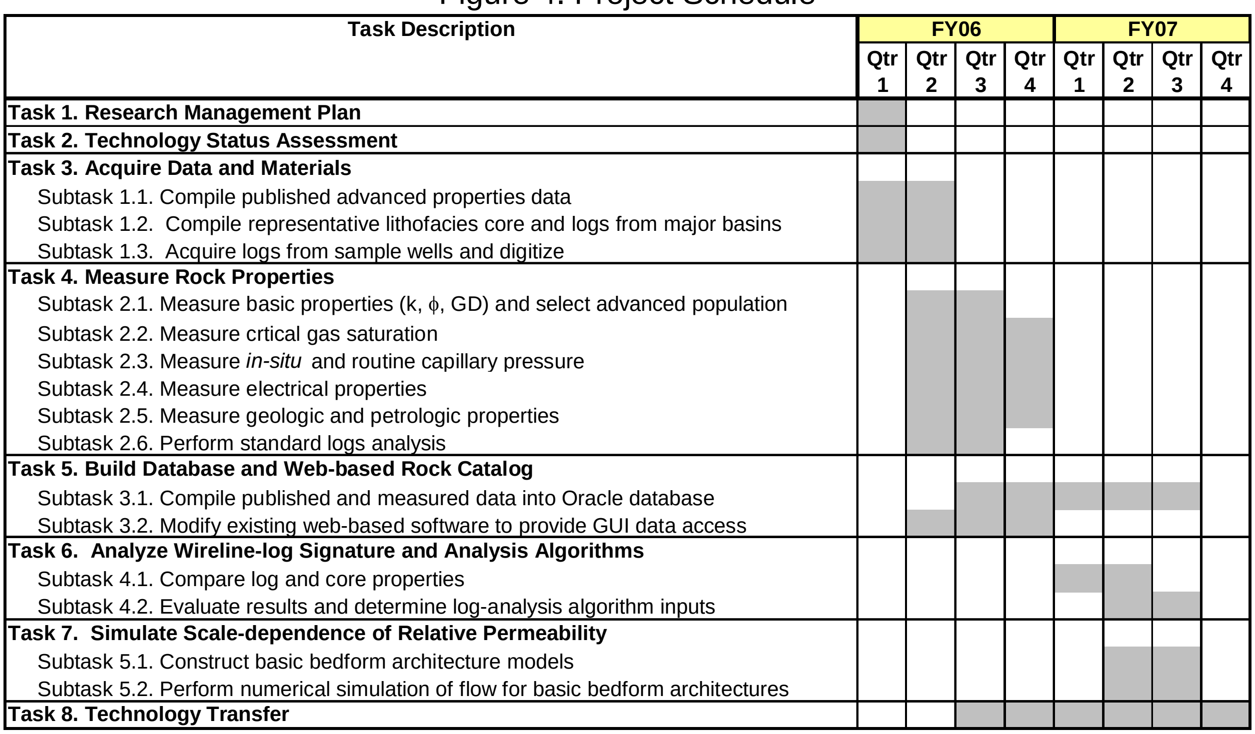
Table1 Labor (months) by Person and Task

	FY06								FY07								
	Task								Task								TOTAL
Personnel (Category)	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	
KGS																	
Alan Byrnes (Core Petrophysics)	0.25	0.25	1.75	3.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	1.25	2.00	1.00	10.00
John Victorine (Software Engineering)	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00
Ken Stalder (Website Management)	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	1.00
Graduate Student	0.00	0.00	2.00	8.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	0.00	4.00	4.00	24.00
The Discovery Group, Inc.																	
Robert Cluff (Sedimentology & Log Petrophysics)	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	1.25	0.00	0.50	4.25
John Webb (Sedimentology)	0.00	0.00	0.50	2.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.50	4.25
TOTAL LABOR	0.25	0.25	5.25	14.00	5.50	0.00	0.00	1.50	0.00	0.00	0.00	0.00	4.50	3.25	6.00	6.00	46.50

2.3 Project Schedule and Milestones

Figure 4 shows the planned project schedule. Most of the database construction and data measurement occurs in the first year.

Figure 4. Project Schedule



2.4 Proposed Travel

Travel is planned for one trip for one person from Kansas to collect petrophysical samples from the US Geological Survey Core Repository in Denver, CO. Local travel for Discovery Group personnel to the Denver core repository is planned. Travel is planned for two people to a DOE/NETL kick-off meeting. Travel is planned for one person each year of the project to attend and make an annual presentation at the DOE/NETL Annual Contractors Meeting. Travel is planned for one person each year of the project to attend and make an annual presentation at the DOE/NETL in Pittsburgh, PA or Morgantown, WV. Travel is planned for one KGS person and one Discovery Group person to attend and present results of research at the 2006 SPE Annual Technical Conference in Houston, TX. Travel is planned for one person from KGS and one person from Discovery Group to attend the 2006 AAPG Annual Meeting in Houston, TX. Travel is planned for one KGS person and one Discovery Group person to attend and present results of research at the 2007 SPE Annual Technical Conference in Houston, TX. Travel is planned for one person from KGS and one person from Discovery Group to attend the 2007 AAPG Annual Meeting in Long Beach, CA.

2.5 Technology Transfer Plan

An active technology transfer program will be undertaken. Technology transfer will be conducted by the KU Energy Research Center (KUERC) and involve KGS staff and Discovery Group staff. The results of the project will be made available to the public and the numerous independent operators producing from western U.S. tight gas sandstone reservoirs. Technology transfer will include access to all data, interpretations and models through flexible online access through the Internet. At least one workshop will be organized through the North Midcontinent

PTTC. Publications and presentations covering various aspects of the project technologies will be an integral part of the technology transfer effort. Presentations will be made to local/regional organizations of independent operators, the DOE, and conferences of professional societies such as the Society of Petroleum Engineers, American Association of Petroleum Geologists, and the Society of Professional Well Log Analysts. All reporting requirements of the DOE, federal agencies, and other governmental entities will be fulfilled in a timely manner.

3. TECHNICAL and MANAGEMENT CAPABILITIES

3.1 Organizational Capabilities and Experience

The **Kansas Geological Survey (KGS)** conducts energy research on a wide range of technical topics (e.g., reservoir characterization, depositional sequence architecture, world wide web-based information transfer, petrophysics) aimed at providing information that can be used to search for additional resources, recover existing resources more effectively, or extend the life of known oil and gas fields. The KGS is a leading provider of Geographic Information System solutions and relational database management systems. The **University of Kansas Center for Research, Inc. (KUCR)** and The **Kansas University Energy Research Center (KUERC)** will administer the project. KUCR is a non-profit corporation affiliated with the University that contracts for all research conducted at the University. Kansas University Energy Research Center (KUERC) coordinates and facilitates integrated energy research at KU. The primary goal is to develop enhanced energy research programs serving state, regional, and national energy needs.

The **Discovery Group, Inc.** has provided services in reservoir characterization, field studies, petrophysics and wireline log analysis, and geologic and stratigraphic analysis to the petroleum industry since 1987 and has extensive working knowledge in North America as well as in Central and South America. The staff has accumulated over 130 years of experience in the oil industry.

3.2 Qualifications of Key Personnel

The principal investigators in this project have over 75 years of combined experience in tight gas sandstone characterization and integration between disciplines. These investigators have previously worked and published together on formation evaluation projects and a tight gas sandstone rock catalog for the Washakie Basin that was part of a proprietary industry project.

Alan P. Byrnes is a petrophysicist with over 25 years of oil and gas industry experience involving core petrophysical analysis, reservoir characterization, and integration with engineering. He has managed several DOE program including the $4.8 million Class II Revisit CO_2 demonstration project in central Kansas (DE-AC26-00BC15124). Alan will manage the project and will be responsible for supervision and measurement of petrophysical properties. **John R. Victorine** has over 23 years of computer programming experience including 12 yrs of Fortran and C programming, 8 yrs of Oracle db, 8 yrs. PL/SQL programming, 3.5 yrs. Java Programming 3 yrs as technical lead on DTIC (Defense Technical Information Center), 2.5 yrs. Lead Programmer in GEMINI, responsible for software development and management in GEMINI. **Robert M. Cluff** is a geologist and petrophysicist with over 25 years experience in oil and gas exploration, development, and research with expertise in the integration of petrophysical and wireline log data, stratigraphy and sedimentology of petroleum reservoirs, and depositional analysis of carbonate and clastic environments. He was the project coordinator for the four-year DOE New Albany Shale project (DE-AC21-76ET12142). **John C. Webb** is a geologist/ petrologist with over 23 years of experience with emphasis on integration of geologic and petrologic data in studies of rock/log/petrophysical characteristics, as applied to formation evaluation of tight gas sands.

3.7 Quality and Suitability of Facilities, Equipment, and Materials

All facilities and equipment necessary for the project are available at KU and the Discovery Group. An abbreviated equipment and software list includes: Computer Systems and Software - The KGS is equipped with a state-of-the-art distributed computer system with the latest workstations, storage devices, routers, and software that presently support a large publicly accessible database and the DOE-sponsored Digital Petroleum Atlas, MIDCARB, and GEMINI projects. Reservoir simulation is performed using the Computer Modeling Group IMEX simulator. Core Analysis Facilities & Equipment - KGS has a fully equipped routine and advanced properties core analysis laboratory capable of performing all the petrophysical measurements defined in the proposed program. Major analytical instruments that will be used in this project include: 1) Routine helium porosimeter; 2) Routine Hassler-type air permeameter; 3) *In situ* Hassler-type triaxial Klinkenberg permeameter; 4) *In situ* Hassler-type triaxial two-electrode electrical resistivity instrument; 5) *In situ* Hassler-type triaxial gas-oil/gas-water/oil-water relative permeameter; 6) Fourteen *In situ* Hassler-type hydrostatic coreholders for obtaining k_{eg}, S_{or} data; 7) 10,000 psi air-mercury capillary pressure instrument. Petrographic Analysis Facilities & Equipment – The KGS and the University of Kansas operate several laboratories with equipment needed for the proposed project, including state-of-the-art transmitted, fluorescence, fluid inclusion, cathodoluminescence microscope.