Oil & Natural Gas Technology

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Semi-Annual Report

GEOMECHANICAL PERFORMANCE OF HYDRATE-BEARING SEDIMENTS IN OFFSHORE ENVIRONMENTS

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Prepared for:
United States Department of Energy
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Office of Fossil Energy

TABLE OF CONTENTS

1. Executive Summary

The objective of this study is to develop the knowledge base and quantitative predictive capability for the description of geomechanical performance of hydrate-bearing sediments (hereafter referred to as HBS) in oceanic environments. The focus is on the determination of the envelope of hydrate stability under conditions typical of those related to the construction and operation of offshore platforms. We have developed a robust numerical simulator of hydrate behavior in geologic media by coupling a reservoir model with a commercial geomechanical code. We are also investigating the geomechanical behavior of oceanic HBS using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation.

We are using data from the literature and we will be conducting laboratory studies in 2007 that generate data to (i) evaluate the conceptual pore-scale models, (ii) calibrate the mathematical models, (iii) determine dominant relations and critical parameters defining the geomechanical behavior of HBS, and (iv) establish relationships between the geomechanical status of HBS and the corresponding geophysical signature. Four organizations, Texas A&M University (TAMU), University of California at Berkeley (UCB), Lawrence Berkeley National Laboratory (LBNL), and Schlumberger (SLB), who are involved in this project..

The milestones for Phase I of this project are given as follows:

- Literature survey on typical sediments containing gas hydrates in the ocean (TAMU)
- Recommendations on how to create typical sediments in the laboratory (TAMU)
- Demonstrate that typical sediments can be created in a repeatable manner in the laboratory and gas hydrates can be created in the pore space (TAMU)
- Develop a conceptual pore-scale model based on available data and reports (UCB)
- Test the developed pore-scale concepts on simple configurations and verify the results against known measurements and observations (UCB)
- Complete the FLAC3D routines that will be linked with the reservoir model (LBNL)
- Complete the TOUGH+/HYDRATE modifications and extensions (LBNL)
- Complete the TOUGH+/FLAC3D interaction interface (LBNL)
- Integrate and test the coupled geomechanical numerical model TFxH/FLAC3D (LBNL)
- Demonstrate that Petrel can be used to develop an earth model for providing data to the TOUGH+/FLAC3D (SLB)

Summary of Pore Scale Modeling by UCB

We have developed a technique for estimating the elastic moduli of a heterogeneous grain pack by modeling mechanical interactions among the grains. Each grain is elastic, and the contact deformations are modeled using Hertz and Mindlin theories. We model the deformation of a grain pack as a sequence of static equilibrium configurations. Each configuration is sought by minimization of the potential energy of the pack. For a loose configuration, our algorithm produces a more realistic tighter pack than other methods. We capture and analyze hysteretic events, such as different loading and unloading responses or abrupt breakage of grain clusters. The computed bulk modulus estimates match experimental values reported in literature. The current progress has been presented at two conferences.

Summary of TOUGH+/FLAC3D Model Development by LBNL

We coupled the TOUGH+/HYDRATE code (developed by LBNL and used for the description of system behavior in HBS) with FLAC3D (a commercial code that is widely used in soil and rock mechanics engineering and for scientific research in academia). TOUGH+/HYDRATE allows the study of flow and transport of fluids (distributed among four phases) and heat in hydrate deposits, and accurately describes the thermodynamics of hydrates as they are distributed among fifteen possible states (i.e., phase coexistence combinations). FLAC3D has built-in constitutive mechanical models suitable for soil and rocks, including various elastoplastic models for quasi-static yield and failure analysis, and viscoplastic models for time-dependent (creep) analysis. The coupled model (hereafter referred to as the TH+/FLAC model) is the first of its kind, can be used for the joint analysis of hydraulic, thermal, flow and geomechanical behavior in HBS, and is a unique tool for the analysis of the effect of hydrate dissociation processes on the structural stability and possible displacement of HBS and of their overburdens.

Summary of Sediment Descriptions and Recommendations by TAMU

Texas A&M University has done a comprehensive literature review to characterize the sediments containing hydrates that have been recovered from scientific cruises. The various regions that have been explored for gas hydrates and were reviewed in our work include Blake Ridge (Offshore South Carolina), Gulf of Mexico, Offshore Oregon (Cascadian Margin and Hydrate Ridge), Nankai Trough (Offshore Japan), Offshore Peru and various other regions explored by the Ocean Drilling Program (ODP). After analyzing all the sediments, we have recommended three sediment mixtures that we can use for mechanical properties testing in Phase II of this project. We have included recipes to make these sediments in the laboratory. We expect that TAMU and LBNL will build these sediments for testing during Phase II so that the results of the laboratory experiments at both institutions can be used seamlessly. As we gain experience in the laboratory, it is possible the 'recipes' and procedures for building the sediments may need to be improved during Phase II of the project.

Summary of Petrel-FLAC3D Interface by Schlumberger

Schlumberger has been developing a method to use Petrel as a platform for entering geologic and reservoir data into the TOUGH+-FLAC3D model when it is completed. There are two requirements for using Petrel to populate FLAC3D with geological surfaces and rock properties. One is to demonstrate that FLAC3D can import surfaces and properties from Petrel. The other is to verify that Petrel can generate the geologic structures characteristic of the hydrate zone offshore. After a series of meetings between Schlumberger and ITASKA, ITASKA has told us they can import properties and surfaces from Petrel. They have demonstrated the ability to import into FLAC3D surfaces generated in Petrel. For the second part, Schlumberger is working internally to characterize geologic structure from 2D seismic lines crossing the hydrate zone in the Gulf of Mexico.

2. Introduction

Gas hydrate is a solid material resulting from the orderly assembly of gas molecules such as methane, carbon dioxide, and hydrogen sulfide, within a clathrate (cage like) structure of water molecules under moderate (relative to conventional oil and gas reservoir conditions) pressure and temperature. Vast amounts of hydrocarbons are trapped in hydrate deposits (Sloan, 1998). Such deposits occur in two distinctly different geologic settings where the necessary low temperatures and high pressures exist for their formation and stability: in the permafrost and in deep ocean sediments near the sea floor.

The three main methods of hydrate dissociation are (1) depressurization, in which the pressure is lowered to a level lower than the hydration pressure P_H at the prevailing temperature, (2) thermal stimulation, in which the temperature is raised above the hydration temperature T_H at the prevailing pressure, and (3) the use of inhibitors (such as salts and alcohols), which causes a shift in the P_H-T_H equilibrium through competition with the hydrate for guest and host molecules (Sloan, 1998). Dissociation results in the production of gas and water, with a commensurate reduction in the saturation of the solid hydrate phase.

Gas hydrates exist in many configurations below the sea floor including massive (thick solid zones), continuous layers, nodular, and disseminated occurrences each of which may affect the seafloor stability differently. The hydrates in all of these configurations may be part of the solid skeleton that supports overlying sediments, which ultimately support platforms and pipelines needed for production from conventional oil and gas resources, and from the eventual production from hydrate accumulations.

During dissociation, the basal zone of the gas hydrate becomes under-consolidated and possibly over-pressured because of the newly released gas (Schmuck and Paull, 1993), leading to a zone of weakness (i.e., low shear strength, where failure could be triggered by gravitational loading or seismic disturbances) that can ultimately result in submarine landslides (McIver, 1977; Paull et al., 1996). Possible mechanisms that can induce dissociation in Hydrate-Bearing Sediments (hereafter referred to as HBS) include an increase in salinity, a drop in the sea level and an increase in the sediment temperature (e.g., by warmer ocean bottom water, or by non-insulated pipes conducting fluids produced from deeper and warmer reservoir) can induce such dissociation.

Hydrate dissociation in HBS produces an enhanced fluidized layer at the base of the gas-hydrate zone. Submarine slope failure can follow, giving rise to debris flows, slumps, slides, and collapse depressions such as described by Dillon et al. (1998). Failure would be accompanied by the release of methane gas, but a portion of the methane is likely to be oxidized unless the gas release is catastrophic. A scenario illustrating submarine slope failure is shown in **Figure 1**. The possible connection between gas-hydrate boundaries and submarine slide and slump surfaces was first recognized by McIver (1982). Several hydrate-related occurrences of oceanic land-slides are discussed in the literature. These include sediment slides and slumps on the continental slope and rise of West Africa (Summerhayes et al., 1979), slumps on the U.S. Atlantic continental slope (Carpenter, 1981), large submarine slides on the Norwegian continental margin (Evans et al., 1996; Bugge et al., 1988), sediment blocks on the sea floor in fjords of British Columbia, and massive bedding-plane slides and rotational slumps on the Alaskan Beaufort Sea continental margin (Kayen and Lee, 1993).

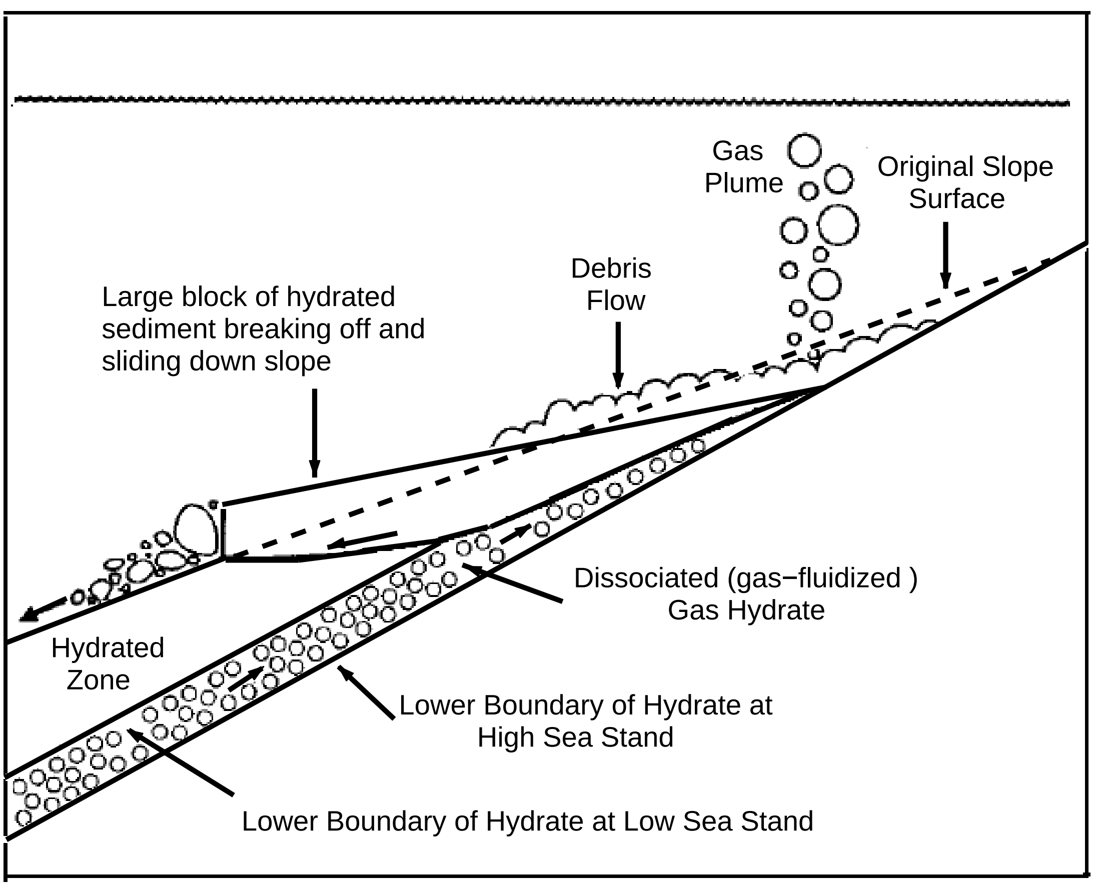

Figure 1 – Diagram showing the effects of gas hydrate dissociation on oceanic hill slope failures and gas release. Adapted from McIver (1982).

For the aforementioned stability concerns, the placement of wells and seafloor platforms associated with oil production is strongly influenced by the presence of gas hydrate on the sea floor or within the sediment lithology. These concerns will be far more pronounced if gas production from oceanic gas hydrate accumulation becomes an economically viable option. Currently, there is a lack of understanding of the mechanical and thermal properties of oceanic sediments containing gas hydrates. The general perception of instability of hydrate-bearing sediments, coupled with the lack of knowledge on the overall geomechanical behavior of such sediments, has resulted in a general strategy of avoidance of such sediments when locating offshore production platforms. By locating production platforms at sites not selected for optimum operation but dictated by the need to avoid the hydrate accumulations, the cost of production can increase significantly. Warmer oil from depth may cause gas hydrate in the neighborhood of a well or pipeline to dissociate, reducing the stability of the supports, and placing significant investments at risk. Such concerns would increase exponentially if gas is to be produced from marine hydrate accumulations, thus posing a serious impediment to the development of such resources.

Few data are available to allow one to manage the risks associated with gas hydrates on the sea floor. Understanding the thermal properties is important because heat transfer through the system is one factor that controls the rate at which the sediments are altered due to hydrate dissociation. Understanding the mechanical properties for a range of hydrate-sediment compositions will allow the prediction of stability and the management of the risks. Measurements of thermal properties have been made of mixed quartz sand and hydrate laboratory samples in addition to pure hydrate samples (Cherskii et al., 1983; Cook and Leaist, 1983; Kneafsey et al., 2005; Moridis et al., 2005a; Stoll and Bryan, 1979; Waite et al., 2002), and strength measurements have been made on laboratory-made pure methane hydrate samples (Durham et al., 2003; Stern et al., 1996). A series of measurements of mechanical, thermal, and electrical properties of tetrahydrofuran hydrate in sediment is underway (Santamarina et al., 2004). Tetrahydrofuran hydrate is stable at atmospheric pressure and near-freezing temperatures; and dissociates to tetrahydrofuran and water without the formation of a gas phase. The applicability of these measurements to the strength of gas hydrate-bearing sediments as would be found below the sea floor has yet to be established. Another study of the mechanical behavior of hydrate bearing sediments concluded that it is essential to collect more data (Hyodo et al., 2005).

The available information is not sufficient to design seafloor platforms or wells (let alone permit the design of future gas production systems from hydrates) in the vicinity of HBS considering the safety, environmental, and economic risks posed by unstable seafloor behavior. We propose to develop the necessary knowledge that will allow the determination of the envelope of safe conditions when locating and operating an offshore production platform for either conventional oil or gas production, or for production from gas hydrates. This knowledge will also provide the necessary tools to evaluate the expected stability performance of hydrate-bearing sediments, and to select optimal sites for production facility installation.

3. Technical Approach

Objective

The main objective of this study is to develop the necessary knowledge base and quantitative predictive capability for the description of geomechanical performance of hydrate-bearing sediments (HBS) in oceanic environments. The focus is on the determination of the envelope of hydrate stability under conditions typical of those related to the construction and operation of offshore platforms.

Scope of Work

To achieve the objectives of the proposed study, the following approach is being employed:

1. The geomechanical behavior of oceanic HBS shall be investigated using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation.
2. Laboratory studies shall be conducted to (i) evaluate the conceptual pore-scale models, (ii) calibrate the mathematical models, (iii) determine dominant relations and critical parameters defining the geomechanical behavior of HBS, and (iv) establish relationships between the geomechanical status of HBS and the corresponding geophysical signature.
3. A robust numerical simulator of hydrate behavior in geologic media shall be coupled with a commercial geomechanical code, thus developing a numerical code for the stability analysis of HBS under mechanical and thermal stresses.
4. Numerical studies shall be conducted to analyze the HBS stability performance under conditions (i) representative of an offshore platform installation and operation, and (ii) typical of oceanic hydrate accumulations under production.

Organizations

There are four organizations initially involved with this project. These four are as follows:

- Texas A&M University (TAMU)
- University of California at Berkeley (UCB)
- Lawrence Berkeley National Laboratory (LBNL)
- Schlumberger (SLB)

4. Project Milestones

Status of Milestones for Phase I as of March 30, 2007

TAMU	Completion of literature survey on typical sediments containing gas hydrates in the ocean	May 2006	Completed and included in Phase I Report
TAMU	Completion of recommendations on how to create sediments in the laboratory	June 2006	Progress made and included in Phase I Report; however, more work will be needed during Phase II
TAMU	Demonstration that typical sediments can be created in a repeatable manner in the laboratory and gas hydrates can be created in the pore space	Sept 2006	Progress made and included in Phase I Report; however, more work will be needed during Phase II
UCB	Development of a conceptual pore-scale model based on available data and reports	July 2006	Completed and included in Phase I Report
UCB	Testing the developed concepts on simple configurations and verification of the result against known measurements and observations	Sept 2006	Completed and included in Phase I Report
LBNL	Completion of FLAC3D routines	Aug 2006	Completed and included in Phase I Report
LBNL	Completion of TOUGH-Fx/HYDRATE modifications and extensions	July 2006	Completed and included in Phase I Report
LBNL	Completion of the TOUGH-Fx/FLAC3D interaction interface	Sept 2006	Completed and included in Phase I Report
LBNL	Component integration and final testing of the coupled geomechanical numerical model TFxH/FLAC3D	Oct 2006	Completed and included in Phase I Report
SLB	Demonstration that Petrel can be used to develop an earth model for providing data to the TOUGH-Fx/FLAC3D	July 2006	Completed and included in Phase I Report

5. Results of Work During the Reporting Period

During the reporting period, there were two major outcomes. **First**, Phase I of the project was completed and the Phase I report was submitted around March 1, 2007 and accepted by the Department of Energy. The **second outcome** was the filing of continuation documents and the negotiation of a revised Statement of Project Objectives (SOPO) and a revised budget for Phase II of this project. The Notice of Financial Assistance Award, a revised SOPO and a revised budget were negotiated and signed by the Department of Energy on April 23, 2007 and then signed by the Texas Engineering Experiment Station (TEES) on May 15, 2007.

Thus, as far as we are concerned, we were not authorized to begin work on Phase II of this project until all contractual documents were signed, which turned out to by May 15, 2007.

Below you will find the Statement of Project Objectives for Phase II.

STATEMENT OF PROJECT OBJECTIVES
(AS MODIFIED MARCH 2007)

GEOMECHANICAL PERFORMANCE OF HYDRATE-BEARING SEDIMENTS IN OFFSHORE ENVIRONMENTS

A. Objective.
The main objective of this study is to develop the necessary knowledge base and quantitative predictive capability for the description of geomechanical performance of hydrate-bearing sediments (hereafter referred to as HBS) in oceanic environments. The focus is on the determination of the envelope of hydrate stability under conditions typical of those related to the construction and operation of offshore platforms.

B. Scope of Work.

To achieve the objectives of the proposed study, the following approach shall be employed:

5. The geomechanical behavior of oceanic HBS shall be investigated using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation.

6. Laboratory studies shall be conducted to (i) evaluate the conceptual pore-scale models, (ii) calibrate the mathematical models, (iii) determine dominant relations and critical parameters defining the geomechanical behavior of HBS, and (iv)establish relationships between the geomechanical status of HBS and the corresponding geophysical signature.

7. A robust numerical simulator of hydrate behavior in geologic media shall be coupled with a commercial geomechanical code, thus developing a numerical code for the stability analysis of HBS under mechanical and thermal stresses.

8. Numerical studies shall be conducted to analyze the HBS stability performance under conditions (i) representative of an offshore platform installation and operation, and (ii) typical of oceanic hydrate accumulations under production.

C. Tasks to be Performed

PHASE I (Budget Period I) – Initial Fundamental Studies and Model Development

Task 1.0 – Research Management Plan (Responsible party: TAMU)

The Recipient shall develop a work breakdown structure and supporting narrative that concisely addresses the overall project as set forth in the agreement. The Recipient shall provide a concise summary of the technical objectives and technical approach for each Task and, where appropriate, for each subtask. The Recipient shall provide detailed schedules and planned expenditures for each Task including any necessary charts and tables, and all major milestones and decision points. This report is to be submitted within 30 days of the award. The DOE Contacting Officer's Technical Representative (COR) shall have 20 calendar days from receipt of the Research Management Plan to review and provide comments to the Recipient. Within 15 calendar days after receipt of DOE's comments, the Recipient shall submit a final Research Management Plan to the DOE COR for review and approval.

<u>Task 2.0 – Technology Status Assessment</u> (Responsible party: TAMU)

The Recipient shall perform a Technology Status Assessment and submit a summary report describing the current state of information and/or technology relevant to the proposed work. The report should include both positive and negative aspects of each existing approach or technology. The report shall not exceed five typewritten pages in length. The report is not to contain any proprietary or confidential data, as the report will be posted on the NETL website for public viewing. The report is to be submitted within 60 days of the award. The DOE COR shall have 20 calendar days from receipt of report to review and provide comments to the contractor. Within 15 calendar days after receipt of the DOE's comments, the contractor shall submit a final Report to the DOE COR for review and approval.

The Technology Status Assessment report shall contain the following:

Current state of information or technology (Note: Industry wide, not strictly the Applicant's technology)

- Summary of Background of Industry/Sector
- Technologies/Tools/Approaches/Data Being Used
- Benefits and Inadequacies of Current State-of-the-Art.

Development Strategies

- Why New Approach is required?
- Problems to Address in this Research Project

Future

- What Barriers will the Research Overcome and the Potential Impact on the exploration or ultimate production of hydrates, or the understanding of the role of gas hydrate in the natural environment.
- Deliverables – Tools, Methods, Instrumentation, Products, etc.

- References (relevant and used in the assessment report)

Task 3 – Fundamental Studies Part I

***Subtask 3.1* - Fundamental studies of pore-scale geomechanical behavior of hydrates in porous media** (Responsible party: UCB)

Recipient shall evaluate the issue of mechanical strength and failure of hydrate sediments. Evaluation shall include:

- Modeling of the impact of hydrate dissociation on mechanical strength of the formation at pore-scale level
- Study of the stress field modification caused by fluid flow and fluid pressure depletion using simulation of the evolution of the rock strength.
- Modeling of formation strength loss using simulation of the process of inter-grain bonds failure and loss of pressure support due to the dissociation.

The study shall involve an extension of the Discrete Element Method (DEM) model of sediments that includes solid grain-hydrate interactions, and shall investigate the macroscopic mechanical properties of the hydrate-solid mixture under stress. Following evaluation of the factors that influence sediment/hydrate mixture mechanics and fracture, the recipient shall investigate the consequences of hydrate destabilization from platform leg pressure, drilling, warm fluid pumping, etc.

***Subtask 3.2* Development of Interface Between Petrel and FLAC3D** (Responsible party: Schlumberger)

The recipient shall develop methods of using the Schlumberger model, Petrel, to develop data sets for use in the FLAC3D and Tough+-Hydrate models. Data sets from seismic surfaces and other sources, such as well logs and core data, will need to be compiled and prepared for use in Petrel. Studies will need to be conducted to determine the type of data required by FLAC3D and how the data can best be supplied using Petrel. Meetings and agreements between Schlumberger and ITASKA will need to be arranged to determine the best scenario for all parties.

***Subtask 3.3* – Description of hydrate-bearing zones as documented by the Ocean Drilling Program and the Chevron-DOE Gulf of Mexico JIP to determine typical gas hydrate bearing sample characteristics** (Responsible party: TAMU)

The Recipient shall coordinate with the Ocean Drilling Program and the Chevron – DOE Deep Water Gulf of Mexico Joint Industry Project to gather information necessary to describe the hydrate-bearing zones encountered by these groups in their drilling and coring operations.

The recipient shall review the analysis of the samples of hydrate-bearing cores obtained by the ODP in the Gulf of Mexico, Oregon, Blake Ridge, and other deep water areas to determine the chemical and mineral characteristics of those samples.

Task 4.0 – Development of the coupled geomechanical numerical model (Responsible party: LBNL funded under a separate Field Work Proposal)

The recipient shall conduct activities necessary to couple the TOUGH+/HYDRATE model for predicting the evolution of pressure, temperature, saturation distribution, and salt concentration in hydrate-bearing systems undergoing changes through any combination of mechanisms that can induce hydrate dissociation or formation (change in pressure, temperature and in the concentration of inhibitors) with the existing geomechanical model FLAC3D (Itasca Consulting Group, 1997) for soil and rock mechanics engineering.

New constitutive models developed in Task 3.2 governing the evolution of macroscopic rock damage shall be implemented into the elastoplastic analysis within the FLAC3D portion of the coupled code. The governing parameters for the rock damage shall be calibrated by numerical analysis of laboratory experiments conducted under Task 7.

Simulations using the coupled code (temporarily named T+H/FLAC), shall execute the two component codes on compatible numerical grids and shall link the component codes through external coupling modules, which serve to pass relevant information between the field equations that are solved in the respective codes.

For modeling of methane hydrates, a TOUGH+/HYDRATE to FLAC3D link shall take multiphase pressures, temperature and concentration inhibitors from the TOUGH+/HYDRATE simulation and provide these to the mechanical analysis in FLAC3D. Special coupling functions shall be developed based on the results of data generated in Tasks 3 and 7. This includes direct effects of temperature and fluid pressure that will induce mechanical deformation through thermal strain and changes in effective stress or swelling. It may also include indirect changes in mechanical properties as a function of temperature and inhibitors.

Additionally a FLAC3D to TOUGH+ link shall take element stress or deformation from FLAC3D and correct factors such as element porosity and permeability. A special coupling module for this link shall be developed based on theoretical or empirical functions that shall be developed during this project. The resulting T+H/FLAC analysis may be *explicit-sequential*, meaning that the porosity and permeability are evaluated only at the beginning of each time step, or the analysis may be *implicit-sequential*, with permeability and porosity updated on the Newton iteration level towards the end of the time step using an iterative process. The explicit-sequential solution should be accurate if the porosity and permeability vary slowly with time or if time step size is relatively small. Additionally, the model shall incorporate novel approaches in the description of spatial propagation (or even cascading) of instability as successively larger areas of the oceanic seafloor fail.

Hydrate-related information (i.e., conceptual models and their mathematical realization, relationships and the corresponding parameters) developed in the theoretical analysis and the laboratory studies of this project shall be incorporated into the T+H/FLAC code as they become available.

In accordance with Section II – Special Terms and Conditions of the Agreement, the Recipient is not authorized to proceed beyond Phase I (Budget Period 1) without the Department of Energy (DOE) approval of a continuation application submitted no later than 60 days prior to the end of the current budget period.

Continuation to Phase II activities will be dependent on satisfactory completion of task work and deliverables associated with Phase I as described above and in the deliverables section.

PHASE II (Budget Period II) – Modeling and Laboratory Measurements

Task 5 - Revised Research Management Plan

The Recipient shall provide an update to the research management plan to reflect the current status of the project, and shall update all aspects of the plan as necessary to accurately define the work to be conducted under the remainder of project activities. The plan shall be submitted within 30 days of the initiation of Phase II. The DOE Contacting Officer's Technical Representative (COR) shall have 20 calendar days from receipt of the Revised Research Management Plan to review and provide comments to the Recipient. Within 15 calendar days after receipt of DOE's comments, the Recipient shall submit a final Research Management Plan to the DOE COR for review and approval.

Task 6 – Fundamental studies of pore-scale geomechanical behavior Part II
(Responsible party: UCB)

The recipient shall verify the model developed in subtask 3.1 by comparing the numerical simulation results against laboratory data (derived from a study in progress at LBNL). The geometry of the pore space shall be obtained either from the computer tomography 3D images of reservoir rock samples (Tomutsa and Radmilovic, 2003; Tomutsa and Silin, 2004) or from simulated HBS (Jin *et al.*, 2004; 2005). Using the principles of upscaling, the micromechanical model shall be translated into a continuum constitutive model, which is suitable as input data in macro-scale numerical simulations. The continuum model shall be derived from a rock damage model (Barenblatt *et al.*, 2002), where the damage parameter is defined as the ratio of the number of failed bonds to the number of unbroken bonds in pristine rock.

The study shall involve an extension of the Discrete Element Method (DEM) model of sediments (Cundall and Strack, 1979) that includes solid grain-hydrate interactions, and shall investigate the macroscopic mechanical properties of the hydrate-solid mixture under stress. Upon completion of evaluation of the factors that influence sediment/hydrate mixture mechanics and fracture, the recipient shall investigate the consequences of hydrate destabilization from platform leg pressure, drilling, and warm fluid pumping.

Task 7 – Developing Data Sets for Hydrate Deposits in Deep Water (Responsible party: Schlumberger)

The recipient shall obtain seismic, log and core data from typical gas hydrate deposits in the deep water Gulf of Mexico and develop data sets using Petrel that can be input into Tough-+/Hydrate-FLAC3D. Recipient shall provide software licenses to TAMU, UCB and LBNL to Petrel and will work with all parties to provide training on the software.

Task 8 – Laboratory studies of basic rock properties in oceanic hydrate bearing sediments

All studies conducted under Task 8 shall be performed using hydrate-sediment samples created according to the methodology and techniques agreed upon through Subtask 8.1 activities. Any intended deviation from the use of the DOE approved sample creation methodology of subtask 8.1 shall be formally requested by the recipient directly to the project COR. The request shall document all necessary justification for the recommended change and shall be provided prior to initiation of the deviation. DOE will review the request and provide concurrence or deny the request within 30 days of receipt of the request.

***Subtask 8.1* – Definition of methodology for creation of Synthetic Hydrate-Sediment mixture samples** (Responsible party: LBNL, funded under a separate Field Work Proposal)

The recipient shall prepare and present to DOE for review and approval (through topical report deliverable from separately funded FWP with LBNL), a detailed description of the methodology and techniques proposed for the creation of synthetic laboratory samples of hydrate bearing sediment in progressively finer grained media, to be used in subsequent laboratory testing (tasks 8.2 – 8.5). The methodology shall identify the chemical and mineral characteristics of the representative samples to be developed and shall define the approach and method of creation planned for each sample set. DOE will review the proposed sample creation methodology and shall provide concurrence with proposed techniques or may request definition of alternate sample creation techniques. The methodology developed under this activity shall be used in the preparation of all samples used to conduct laboratory testing under the remaining Task 8 activities.

****GO/NO-GO DECISION POINT****

The Recipient shall not proceed beyond Subtask 8.1 of this award without written authorization from the Contracting Officer. Refer to the "DOE Responsibilities" provision contained under "Statement of Substantial Involvement (Oct 2004)" of this Cooperative Agreement.

In order to meet the requirements for proceeding beyond the Decision Point, the recipient must prepare, present and have approved by DOE, a detailed description of the methodology and techniques proposed for the creation of synthetic laboratory samples of hydrate bearing sediment in progressively finer grained media, to be used in subsequent laboratory testing (tasks 8.2 – 8.7). The methodology shall identify the chemical and mineral characteristics of the representative samples to be developed and shall define the approach and method of creation planned for each sample set. DOE will evaluate the viability of the

proposed methodology and will re-evaluate the focus of overall project objectives and remaining Task 8 activities based on the anticipated hydrate – sediment sample creation capabilities.

***Subtask 8.2* Production of large-scale cores of artificial hydrate-bearing sediments using the techniques developed by LBNL** (Responsible Party: LBNL funded under a separate Field Work Proposal)

The Recipient shall conduct a series of laboratory geomechanical and geophysical experiments on synthetic hydrate-sediment mixture samples (using samples created according to the methodology defined and approved in Subtask 8.1) to establish the relationships between measured geophysical attributes and changes in mechanical properties that affect the hydrate-bearing seafloor stability, with the intention of better defining multiphase systems in HBS under relatively low confining stresses.

***Subtask 8.3* Study the geomechanical properties in high-P, low-T triaxial cells, with simultaneous CT X-ray imaging** (Responsible Party: LBNL funded under a separate Field Work Proposal)

The Recipient shall conduct laboratory triaxial compression tests on synthetic hydrate-bearing cores (produced according to the methods defined and approved under Subtask 8.1) to determine the fundamental geomechanical strength parameters (Mohr-Coulomb failure envelope).

This test shall be conducted for a selected number of material parameters, including initial sediment porosity, hydrate saturation, pore pressure, and temperature. The tests shall be conducted on samples made up of progressively finer grained, hydrate bearing media to begin with fine sand and progress through clay or silica flour.

The recipient shall examine the impact of long-term loading on the sample strength by the creep test.

In the event that samples required for the tests identified cannot be effectively created using the methodology defined in Subtask 8.1, the sample creation methodology and / or the focus of remaining laboratory tasks may be re-evaluated through detailed discussions between the recipient and DOE. No change to the planned approach should be undertaken without explicit DOE approval.

Subtask 8.4 **Determine the geophysical signature of hydrates in porous media, and the effects of thermal and loading stresses** (Responsible Party: LBNL funded under a separate Field Work Proposal)

Using samples with the same compositions as those used in Subtask 8.3 for the geomechanical testing, the Recipient shall conduct a series of laboratory acoustic property measurements.

The recipient shall use a new, low-frequency resonant bar device that is capable of determining the acoustic properties from a small core sample. Using this device, both P (compressional) and S (shear) wave velocities and attenuation of the sample shall be determined at frequencies near 1 kHz. Such measurements shall be conducted continuously as the hydrate in the HBS cores dissociate under controlled conditions.

Subtask 8.5 Validation of Coupled Geomechanics/Flow Code (Responsible Party: LBNL funded under a separate Field Work Proposal)

The recipient shall compare results and data from the performance of a laboratory deformation test on a hydrate bearing sediment with numerical predictions for the same experiment completed using the T+H/FLAC code.

The experiment shall initially be designed using T=H/FLAC to optimize location and frequency of measurements. The experiment shall involve a hydrate bearing sample first subjected to triaxial stress and subsequently dissociated under a constant stress. Axial deformations of the sample caused by changes in sample strength and elastic moduli changes shall be measured. If appropriate, this test will be performed using CT scanning to examine sample uniformity.

The test shall include independent parameter estimation (including comparisons to earlier laboratory measurements of the same parameters). The level of validation of the T+H/FLAC code achieved through this comparison shall be based on the agreement of observed (lab experiment) and predicted (numerical simulation) system behavior in addition to the proximity of measured and deduced parameters.

Subtask 8.6 Initial predictive studies of hydrate bearing sediment stability (Responsible Party: LBNL funded under a separate Field Work Proposal)

The recipient shall initiate activity focused on application of the coupled T+H/FLAC code to a series of realistic geomechanical problems of progressively increasing complexity in hydrate-bearing media. This effort shall include the training of students from TAMU (and potentially UCB) on the use of the T+H/FLAC code by its developers at LBNL and shall include the identification and description (in terms of geological models) of the problems to be investigated.

In accordance with Section II – Special Terms and Conditions of the Agreement, the Recipient is not authorized to proceed beyond Phase II (Budget Period 2) without the Department of Energy (DOE) approval of a continuation application submitted no later than 60 days prior to the end of the current budget period.

Continuation to Phase III activities will be dependent on satisfactory completion of task work and deliverables associated with Phase I and II as described above and in the Deliverables section .

PHASE III (Budget Period II) – Integration of Models and Data

Task 9 - Revised Research Management Plan (Responsible Party: TAMU)

The Recipient shall provide an update to the research management plan to reflect the current status of the project, and shall update all aspects of the plan as necessary to accurately define the work to be conducted under the remainder of project activities. The plan shall be submitted within 30 days of the initiation of Phase III. The DOE Contacting Officer's Technical Representative (COR) shall have 20 calendar days from receipt of the Revised Research Management Plan to review and provide comments to the Recipient. Within 15 calendar days after receipt of DOE's comments, the Recipient shall submit a final Research Management Plan to the DOE COR for review and approval.

Task 10 – Predictive studies of hydrate bearing sediment stability performance under conditions representative of an offshore platform installation and operation. (Responsible Party: LBNL [funded under a separate Field Work Proposal], TAMU, UCB)

This study will have several stages. Initially, small subcomponents of the system shall be studied. With the knowledge gleaned from the first stages of the study, progressively larger and more integrated components shall be studied. These studies shall be conducted using the T+H/FLAC code (see Task 4), and shall be conducted mainly by TAMU and UCB graduate students with significant input and strong involvement of LBNL.

***Subtask 10.1* Effect of structure weight on the geomechanical properties and stability performance of HBS in oceanic sub-floors in the immediate vicinity of platform**

anchors and/or foundations. (Responsible Party: UCB, SLB and LBNL [funded under a separate Field Work Proposal])

The recipient shall apply the coupled model developed in Task 4 to investigate the influence of factors and parameters such as the hydrate saturation, type of sediment, position of the HBS in the subsurface relative to the anchoring/foundation location, structure weight, and initial pressure and temperature conditions on the geomechanical properties and stability performance of HBS.

Subtask 10.2 **Effect of heat exchange with non-insulated fluid production pipes on the geomechanical properties and stability performance of HBS.** (Responsible party: UCB, SLB and LBNL [funded under a separate Field Work Proposal])

The recipient shall apply the coupled model developed in Task 4 to investigate the potential effects of heated well bores (employed to avoid hydrate formation in gas producing systems) on geomechanical properties and stability performance of HBS.

Subtask 10.3 **Effect of gas production from oceanic hydrate accumulations on the HBS geomechanical stability, with particular emphasis on sloping oceanic terrains.** (Responsible party: TAMU, SLB and LBNL [funded under a separate Field Work Proposal])

The recipient shall apply the coupled model developed in Task 4 to evaluate scenarios concerning how production of natural gas from or near sediments containing gas hydrate deposits will affect the geomechanical stability of the seafloor in both the short term and the long term.

Subtask 10.4 **Long-term potential damage to wells and pipes located within HBS as a result of (i) the geomechanical properties and displacement tendencies of HBS, and (ii) the effects of the issues discussed in 8.2 to 8.4**. (Responsible Party: UCB, SLB and LBNL [funded under a separate Field Work Proposal])

The recipient shall apply the coupled model developed in Task 4 to evaluate scenarios concerning how sediments containing gas hydrates can affect sea floor stability and potential damage to wells and pipes located in or near the HSB in both the short term and the long term.

Subtask 10.5 **Integration of the localized studies in Tasks 8.1 to 8.4 in the evaluation of the large-scale stability of the hydrate-bearing oceanic sub-floor formations.** (Responsible Party: TAMU)

The recipient shall apply the coupled model developed in Task 4 to evaluate issues involving seafloor stability combining the knowledge generated in Tasks 8.1 through 8.4 plus knowledge of field situations documented in the literature.

Subtask 10.6 **Hydrate Stability Performance During Production and Its Impact on Borehole Stability and Well Casings.** (Responsible Party: Schlumberger)

The recipient shall conduct activities necessary to develop a study which shall use the elastoplastic and/or damage-based constitutive model identified in Task 3 to evaluate well bore stability and casing integrity in the presence of hydrate dissociation and production.

- Modes of casing failure (tension, buckling, shear, etc.) that could occur under producing conditions shall be considered.
- A workflow shall be established which shall allow inversion of acoustic dipole dispersion measurements as described by Plona et al (2002) for the state of damage and then to use this both to monitor hydrate dissociation and production and to predict well bore stability and casing integrity.

D. Deliverables

In addition to the reporting requirements specifically detailed in the Federal Assistance Reporting Checklist (DOE F 4600.2) the following additional topical reports or other deliverables are required.

General

In addition to the reports required by the "Federal Assistance Reporting Checklist" and those described specifically below, the Recipient shall submit monthly informal e-mail status reports directly to the project COR. The monthly e-mail reports shall contain a short description of successes, advances and problems encountered. The report should not exceed one (1) page in length per task and shall be submitted via e-mail only.

Phase I (Budget Period I)

- **Task 1**: A Research Management Plan as described in Task 1 shall be submitted within 30 days from the project award.
- **Task 2**: A Technology Status Assessment as described in Task 2 shall be submitted within 60 days from the project award.
- **Task 3**: (Subtask 3.1 – 3.3) A topical report shall be submitted including details as necessary to thoroughly describe:
  - the development of a pore-scale model of geomechanical behavior of a hydrate-bearing formation in an oceanic environment,
  - the formulation of basic concepts of a continuum rock damage model and
  - the characteristics of sediments in the ocean floor containing gas hydrates using the information from the Ocean Drilling Program and the Chevron-DOE JIP
- A topical report detailing all activities conducted by both recipient and subcontractors under Phase I shall be submitted 15 days prior to the completion of Phase I. The report shall provided detailed description of all work undertaken, the methods used to conduct the work , data and information resulting from this work, descriptive analysis of results and conclusions to be drawn from results. Information contained in the report should cover specifically Tasks 3 – 4 including all subtasks and shall include, as part of the report, or as appendices, all supporting documentation (software code, drawings, maps etc).

The report shall also include applicable information made available from national laboratory partner (LBNL) on activities conducted under separately funded Field Work Proposal which are considered a part of overall project activities as defined in the task descriptions above. Finally the report shall provide a listing of all professional publications, technical papers and/or presentations generated as a result of project activities.

Phase II (Budget Period II)

- **Task 5**: A Revised Research Management Plan as described in Task 5 shall be submitted within 30 days of the start of Phase II (Budget Period II)
- A topical report (submitted by LBNL as deliverable under separately funded FWP) detailing the chemical and mineral characteristics of the representative hydrate bearing samples to be developed and defining the approach and method of creation planned for each sample set.
- A topical report detailing all activities conducted by both recipient and subcontractors under Phase II shall be submitted 15 days prior to the completion of Phase II. The report shall provided detailed description of all work undertaken, the methods used to conduct the work , data and information resulting from this work, descriptive analysis of results and conclusions to be drawn from results. Information contained in the report should cover specifically Tasks 6-8 including all subtasks and shall include, as part of the report, or as appendices, all supporting documentation (software code, drawings, maps etc). The report shall also include applicable information made available from national laboratory partner (LBNL) on activities conducted under separately funded Field Work Proposal which are considered a part of overall project activities as defined in the task descriptions above. Finally the report shall provide a listing of all professional publications, technical papers and/or presentations generated as a result of project activities.
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Phase III (Budget Period III)

- **Task 9**: A Revised Research Management Plan as described in Task 9 shall be submitted within 30 days of the start of Phase III (Budget Period III)
- A topical report detailing all activities conducted by both recipient and subcontractors under Phase III shall be submitted 15 days prior to the completion of Phase III. The re-

port shall provided detailed description of all work undertaken, the methods used to conduct the work , data and information resulting from this work, descriptive analysis of results and conclusions to be drawn from results. Information contained in the report should cover specifically Tasks 6-8 including all subtasks and shall include, as part of the report, or as appendices, all supporting documentation (software code, drawings, maps etc). The report shall also include applicable information made available from national laboratory partner (LBNL) on activities conducted under separately funded Field Work Proposal which are considered a part of overall project activities as defined in the task descriptions above. Finally the report shall provide a listing of all professional publications, technical papers and/or presentations generated as a result of project activities.

E. Briefings/Technical Presentations

Briefings and presentations shall be presented as follows:

Phase I (Budget Period I)

- A Kickoff Meeting at the beginning of Phase I (Budget Period I);
- One annual briefing for presentation to the COR, detailing plans, progress and the results of the technical effort at the National Energy Technology Laboratory (NETL);
- One presentation detailing work by recipient and all subcontractors at annual Department of Energy (DOE) Contractor Review meeting to be held at the NETL site or outside technical conference (to be determined by mutual agreement of the Recipient and the NETL Contracting Officer's Representative).

Phase II (Budget Period II)

- One annual briefing for presentation to the COR, detailing plans, progress and the results of the technical effort at the National Energy Technology Laboratory (NETL);
- One presentation detailing work by recipient and all subcontractors at annual Department of Energy (DOE) Contractor Review meeting to be held at the NETL site or outside technical conference (to be determined by mutual agreement of the Recipient and the NETL Contracting Officer's Representative).

Phase III (Budget Period III)

- One annual briefing for presentation to the COR, detailing plans, progress and the results of the technical effort at the National Energy Technology Laboratory (NETL);
- One presentation detailing work by recipient and all subcontractors at annual Department of Energy (DOE) Contractor Review meeting to be held at the NETL site or outside technical conference (to be determined by mutual agreement of the Recipient and the NETL Contracting Officer's Representative).

6. Conclusions from the Reporting Period

On the basis of the work performed during this reporting period, the following conclusions are presented.

- Phase I was completed and the Phase I Report was submitted to the Department of Energy around March 1, 2007.

- The Notice of Financial Assistance Award, the Statement of Project Objectives and the revised budget for Phase II were developed and approved by the Department of Energy on April 23, 2007 and by the Texas Engineering Experiment Station on May 15, 2007.

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