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Coalbed Methane: Important Source of Natural Gas Resource

Submitted by Satya Harpalani (Mining Department, Southern Illinois University Carbondale) and Shimin Liu (Mining Department, Penn State University)

Coalbed methane (CBM) has become an important part of the world's natural gas resource. The energy industry classifies coal as an "unconventional gas reservoir" and has worked continuously towards developing methods to economically develop gas production from it. Most recent data from the Energy Information Administration (EIA) states that proven CBM reserves of the U.S. accounted for about 17.5 trillion cubic feet (TCF) in 2010. Production of CBM in 2010 was 1.9 TCF, accounting for 8.5% of the U.S. natural gas production. In addition, interest in other countries -- particularly Canada, Australia, China and India -- continues to grow. Interest in CBM is not only based on the production potential, but also because the U.S. Environmental Protection Agency (EPA) identifies methane as a "greenhouse gas," known to be significantly more damaging to the environment than carbon dioxide.

CBM Reservoir Characteristics and Production Mechanism

Coal deposits act as self-sourced natural gas reservoirs wherein the three crucial elements of a petroleum system (source rock, reservoir and trap) are located together in a single geological unit. Methane is generated during the process of coalification, either by biogenic or thermogenic routes. Once generated, the methane gets adsorbed on to the internal surface of coal matrix or is compressed in the void space within coal. Gas storage capacity in coal depends on the in situ pressure and adsorbed gas content -- typically quantified by the Langmuir sorption isotherm, established using crushed coal samples in the laboratory.

Gas transport in coal seams is commonly understood as three hydrodynamic mechanisms by taking the dual porosity nature of coal into account: desorption of gas from the internal coal surface, followed by diffusion through the coal matrix bounded by the cleat and, finally, laminar flow through the naturally occurring fracture network, known as the cleat system. The migration process of methane in the coal seam is shown schematically in Figure 1.

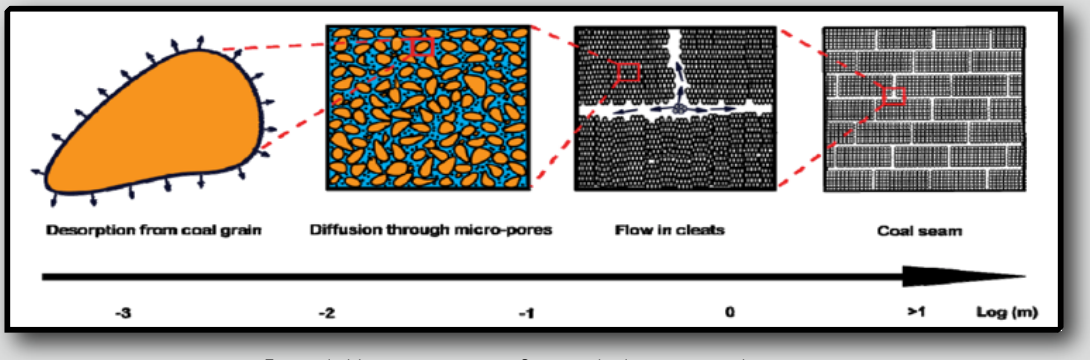

Figure 1: Migration process of gas in dual porosity coal seams

The standard practice to produce CBM is by pressure depletion and, as the name suggests, involves depressurizing the coal. Since most CBM reservoirs in the U.S. are water saturated initially, it is necessary to pump this water out to reduce the coal seam pressure. Because of the unique gas storage and migration mechanisms, the pressure decrease results in desorption when the pressure in the coal seam falls below a certain level. Once desorption occurs, methane moves towards the cleat system. In the cleat system, there are three stages for flow in CBM reservoirs: (a) single-phase water flow during dewatering when only water is mobile in the cleat system while the reservoir pressure decreases; (b) non-saturated single-phase water flow – as soon as the reservoir pressure drops below the desorption pressure, gas migrates towards the cleat systems but it cannot move since it exists as isolated bubbles; (c) gas and water two phase flow – gas flow starts with further reduction in reservoir pressure and gas relative permeability increases with depletion.

- ***Continued on Page 2*** -

TECH Note

Coalbed Methane: Important Source of Natural Gas Resource (continued)

The changes in gas/water saturation in cleats result in fluid mobility changes in the cleat system, leading to a unique feature observed during CBM production -- a negative gas decline rate. The gas production rate initially increases to a peak production rate as the seam dewaters and the relative permeability to gas increases. After the peak rate, it is followed by a normal decline in production rate as reservoir pressure decreases with continued production. The three production stages are shown in Figure 2.

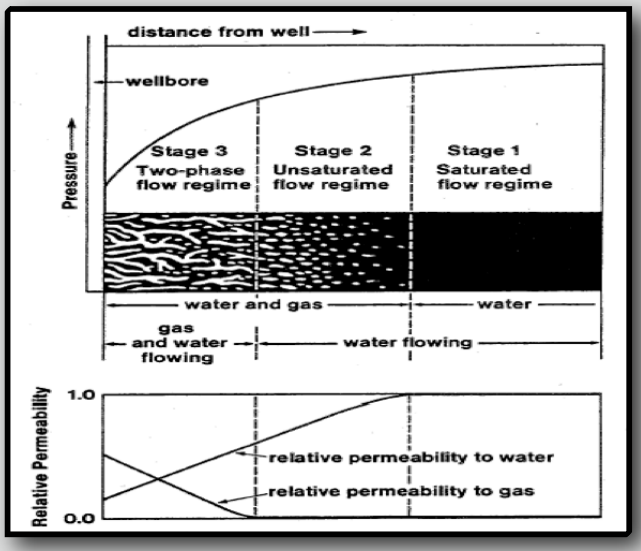

Figure 2: Three stages of coalbed gas production.

Challenges of CBM

A CBM reservoir has several unique features which lead to a rather complex nature of reservoir formation evaluation and modeling -- the two keys for optimized development of CBM production. Rock/geo-mechanics plays an important role in both. From a geo-mechanical point of view, significant effort has been made in the area of conventional reservoirs, e.g., stress-strain relationship during depletion, failure mechanics of formation, solid production, compaction and subsidence, mechanics of hydrofracturing, etc. However, for CBM reservoir engineering, there are areas with significant uncertainties and a need for further research.

Dynamic changes in the reservoir stress field during gas production are still somewhat unclear. The reservoir stress is expected to change dynamically and passively with gas and water depletion. A sound knowledge of the stress profile associated with deformation resulting from depletion is critical for several reasons. The ones that are well known are problems associated with permeability increase due to loss in horizontal stress that can significantly enhance the permeability and promote gas production. An exponential relationship between stress and permeability is widely used in the CBM reservoir modeling. In order to predict permeability accurately, the stress variation must be known with confidence over the depletion period. Thus, a clear picture of the dynamic stress profile is worth studying further.

Reservoir pressure depletion induces continuous changes in the formation stress-- not only in effective but also in the total stress. This might possibly result in failure of both reservoir formation and production wells. The unique feature of desorption of coal causes an extra strain with gas depletion, which is referred as coal matrix shrinkage. This additional strain can lead to a significant stress loss if the geometric boundary is assumed to remain fixed during depletion. The mechanical behavior of CBM reservoirs, therefore, is very different from that of conventional sandstone gas reservoirs and additional effort is needed in the future.

Recent laboratory studies have demonstrated that coal becomes stiffer with an increase in confining stress and the moduli of coal are not constant parameters with respect to effective stress. Depressurizing a reservoir automatically triggers changes in effective stress and changes of coal moduli should be taken into account during a reservoir formation evaluation process. Moreover, the geo-mechanical properties -- such as Young's modulus, cohesion, or angle of internal friction -- may also change with gas pressure and temperature during depletion. However, this behavior is not well understood at this time. Finally, anisotropy of coal formation needs extra attention on flow behavior simulation as well as coupling process between fluid flow and solid deformation.

Future of CBM

Almost forty countries have initiated CBM activity of some type. Active drilling programs are either in progress or have been in the past in at least twenty nations. In the near future, the CBM industry may also take a new direction, becoming an essential player in carbon sequestration. A few enhanced coalbed methane (ECBM) pilot projects have been carried out in depleting CBM fields as candidates for CO_2 storage sites. ECBM technique offers the opportunity of removing greenhouse gases and simultaneously increasing the production of natural gas. Currently, CBM is still labeled as "unconventional natural gas." However, new technologies and techniques have created an atmosphere in which producing gas from coal is a global reality and it is a matter of time before it is labeled as a conventional source of energy.

Future Leaders

ARMA Future Leaders

Submitted by David J. Scarpato, Haley & Aldrich, Inc

The concept for the Future Leaders Program was developed by the ARMA Board of Directors (BOD) as a way to keep younger career-focused members engaged with ARMA activities and involved in the long-term direction of the organization. There are currently 18 ARMA members actively involved in the program, serving a term lasting three years.

The first class of ARMA's future leaders met at the 2012 symposium in Chicago in June. The Chicago meeting was a chance for the leaders to become acquainted with one another, meet senior ARMA members, and discuss goals for the upcoming year. Many of the leaders were intimately involved with the 2012 ARMA symposium, and assisted with paneling judges for the poster awards committee, acted as session developers or moderators, and as technical paper reviewers.

There is quite a wide range of technical backgrounds represented in the current class of future leaders, from petroleum engineering to geology to mining engineering and civil engineering. The leaders comprise representatives of academia and private companies. Many of the leaders reflect a range of national origins and are working on international projects. All of this is a great tribute to just how diverse ARMA has become over the last decade.

Since program inception in June 2012, the leaders have been involved with the following tasks:

- Developing the concept of a job posting "board" and/or "career center" at the 2013 symposium, as a way for younger members to have real-time access to potential career and networking opportunities;
- Assisting with concepts for ARMA web page development;
- Developing sessions for the ARMA 2013 symposium in San Francisco;
- Reviewing papers for the ARMA 2013 symposium;
- Attending the October 2012 BOD meeting in Salt Lake City, Utah;
- Developing concepts that increase ARMA membership, through corporate memberships and diversification of members/attendees; and
- Contributing to the ARMA newsletter.

In addition to their involvement with ARMA, many of the future leaders are involved in cutting-edge research and tackle complex project assignments in their "day jobs." Most of the leaders are in their late 20's through mid 30's, which is a busy time in a young professional's life -- balancing work, finances, and family demands -- as many members can attest. This freshman crop of future leaders is certainly busy!

Other younger members will be given the chance to become involved with the program when the next nomination period begins in early 2014. Those that want to learn more about the Future Leaders Program are encouraged to contact the leaders themselves (See list of members in the sidebar.)

Future Leaders Roster

Alvin W. Chan
Shell

Chandong Chang
Chungnam National University

Brian Crawford
ExxonMobil

Murali Gadde
Peabody Energy

Paul Hagin
Chevron ETC

Gang Han
Hess Corporation

Amie L. Hows
Shell

Haiying Huang
Georgia Tech

Justin Hustoft
RESPEC Consulting & Services

Thierry Lavoie
Itasca Consulting Group

Ellen Mallman
BP

Michael Murphy
NIOSH Pittsburgh Research Center

Marisela Sanchez-Nagel
Itasca Consulting Group

Maria-Katerina Nikolinakou
Bureau of Economic Geology - University of Texas

Lance A. Roberts
RESPEC Consulting & Services

Azadeh Riahi
Itasca Consulting Group

David J. Scarpato
Haley & Aldrich

Karim Zaki
Chevron ETC

ARMA
Forum

"Rheology, Creep and Viscoplasticity: It's About Time" An ARMA Forum

ARMA is pleased to announce that a multidisciplinary forum on rheology, creep, viscoplasticity, and their applications will be held on 18-19 March 2013 in Salt Lake City, Utah. The forum is open to all; details on how to access the forum are below.

What is Rock Rheology?

Rheology relates the macroscopic response of a material to the forces that act on it. The rheologic characteristics of a rock, the effective stress field, and the appropriate boundary conditions determine deformation. Rheology is central to all aspects of rock mechanics, geomechanics and geoscience.

ARMA Forum

While rheologic properties of rock or soil and their engineering implications are common concerns for nearly every geoscientist/ engineer, rheology is a topic that receives less coverage than some more glamorous, topical subjects do. Ironically, understanding many of these topical subjects hinges on appreciation of constitutive and rheologic behavior of rock or soil. The purpose of this workshop is to provide updates of recent rheologic developments, to determine relevant research and development domains, to introduce or clarify engineering implications, and to share field and laboratory experience.

In geomechanics and rock mechanics, there is a renewed and growing interest in time-rate dependency of the deformational behavior of geologic materials. The study of instabilities in the earth's crust and near-surface strata, safety in man-made excavations, and in petroleum extraction requires understanding of inter-relationships among stress, strain, pore fluids, temperature, and their relative time-rates of change. Earthquake engineering, tectonics, seismic and micro-seismicity are crosscutting technologies. This forum addresses these aspects of rock rheology from the perspectives of three areas:

1. Laboratory and field measurements;
2. Numerical considerations – from simple to complex rheology; and
3. Field applications and case studies

Who Should Attend?

The forum will encompass rheological considerations in three technical disciplines, each interwoven with geologic and geophysical insight. An objective is to allow interactions among colleagues whose specialties are somewhat different but who have insight into rheologic behavior. For example:

Geosciences/Geomechanics: Recent advances in viscoplasticity are focused on nano- and micro-strains, and their effects on the microstructural fabric of rocks. How do we scale up, from local grain- and pore-level strains to macro- and meso-scales of mineral/ rock assemblages? How and when do subseismic microstrains propagate into detectible, locatable, dynamic micro- and macroseismic events? How do we populate the properties of large-scale geocellular models with relevant petrophysical and viscoplastic properties? How do we link multifaceted components towards a practical common-earth model?

Civil: Has consolidation theory advanced substantially? How do we view rheology and effective stress concepts – or do we? How do these improve the reliability of calculated factors of safety in various geotechnical structures? How can we improve static and dynamic structural models towards realistic, proactive risk assessment tools?

Mining: How can structural geology and rheological insight help? How do we extend ground-reaction concepts to improve predictive models of mine openings, mine-bumps, cavings, stability of pit-slopes and tailings ponds?

Petroleum: How can fracture mechanics, structural geology and rheology be better enfranchised into well construction, production and reservoir management? How do we include flow-coupling mechanisms in "shale reservoirs" during brittle-ductile transition, creep of hydraulic fractures, and in containment prediction? Subsidence prediction, subsalt drilling, and deepwater reservoirs also require viscoplasticity in their geomechanical models. Earthquake engineering and microseismicity are crosscutting technologies that require rheologic characterization. Don't forget the rheologic behavior of oil sands subjected to steam flooding (e.g., SAGD).

Students, faculty, professionals and researchers are encouraged to participate. Professional Development Hours will be available.

Forum Details

Where: University Park Marriott Hotel, Research Park, Salt Lake City, Utah, USA.
When: Monday & Tuesday, 18-19 March 2013, with a welcoming reception on Sunday, 17 March 2013.
Cost: $350 for registration and meals. Rooms will be at a conference rate.
For Information: Visit www.armarocks.org/forum.html
Peter Smeallie (ARMA): smeallie@armarocks.org 1-703-683-1808
John McLennan (University of Utah): jmclennan@egi.utah.edu or 1-801-587-7925

ARMA Symposium

Symposium Back in San Francisco

The winter snows may be swirling, but more than 600 authors are busily preparing papers for presentation at the 47th U.S. Rock Mechanics/Geomechanics Symposium. This year, the event will be held in San Francisco from 23-26 June; this annual event promises to continue to meet the standard set by previous symposia, with outstanding technical content, discussion of current topics of academic and professional interest, and the opportunity to catch up and share professional experiences with friends and colleagues.

We have had a record response to our call for papers. We accepted 624 abstracts from those submitting. The abstracts originated from 38 countries and represent a wide and varied range of issues concerning rock mechanics and geomechanics, including relevance to societal issues such as sustainability. (See the range of paper themes presented in the sidebar.)

We have assembled a great docket of featured speakers. The lineup so far includes Sally Benson (Stanford University) speaking on carbon dioxide capture and storage, followed by a presentation by Chris Breeds (Subterra, Inc.) on the history and restoration of the Dead Sea and the Lower Jordan River. Another speaker scheduled for the symposium is Erik Eberhardt (University of British Columbia), who will present an integrated approach to improving our understanding and assessment of deep-seated rock slope hazards.

Two informative full-day workshops will be presented prior to the symposium. The first is titled "Recent Advances in Geomechanics Toward Solution of Technical, Environment and Economic Challenges in Unconventional Resources." The second is listed as the "2nd ISRM-ARMA Workshop on Petroleum Geomechanics Testing."

There are four options for short courses. Topics will include: "Reliability Engineering for Tunnel Construction;" "Geomechanical Considerations for Unconventional Hydrocarbon Developments: Evaluating the Role of Natural Fractures and Microseismicity;" "Analysis and Design of Foundations on and in Rock;" and "Numerical Modeling of Cave Mining."

Attendees will also want to take advantage of some of the unique sites in the region. The following technical tours (tentative) are being planned:

- **The Geysers / Napa Valley:** Visit the Geysers, one of the largest geothermal power operations in the world and site of a recent Enhanced Geothermal demonstration project. The return trip to San Francisco will include a stop at a Napa winery.
- **San Andreas Fault Zone:** Tour surface expressions of the mighty San Andreas Fault, at various locations along the San Francisco peninsula.
- **Santa Cruz Geology:** View sandstone intrusions, paleostress indicators, hydrocarbon fronts, dike sill complexes, and carbonate cold seep structures -- all along the beautiful Santa Cruz coastline.
- **Lawrence Berkeley Laboratory and Richmond Field Station:** See the latest high-tech laboratory testing techniques in use at Lawrence Berkeley National Laboratory, as well as the large-scale geotechnical test facilities at the UC Berkeley Richmond Field Station (site of future LBL expansion).

If you have ideas, comments, or suggestions relating to the Symposium, please contact organizers through info@arma.org.

Themes of Submitted Papers

Coal Mining Rock Mechanics
Deep Rock Mining
Ground Control
Mining Seismicity
Numerical Modeling of Coal Mining
Rock Mechanics of Cave Mining
Rock Mechanics of Weak Rocks and Evaporites
Other Mining

Petroleum Engineering
4D Geomechanical Modeling
Constitutive Modeling
Coupled Processes Modeling
Experimental Rock Mechanics
Fracture Containment and Cap Rock Integrity
Geomechanics for Depleting Reservoirs
Geomechanics for Unconventional Resources
Hydraulic Fracture Monitoring
Injection and Fracture Mechanics
Multiphysics Flow Modeling in Fractured Rocks
Pore Pressure and In Situ Stress Prediction and Modeling
Reactive Transfer in Geomechanics
Wellbore Stability
Other Petroleum

Civil Engineering
Dams and Foundations
DDA Methods
Discrete Geomechanics
Earthquakes and Seismicity
Environmental
Fracture Statistics and DFN
Geothermal
Grouting and Support
In-situ Measurements
In-situ Stress
Rock Mass Characterization
Rock Mass Constitutive Modeling
Rock Slopes
Rock Testing
Tunnel and Caverns
Other Civil

Interdisciplinary Topics
CO_2 Sequestration and Utilization
Geologic Repository Issues for Nuclear Waste Disposal
Geomechanical Challenges Associated with Geothermal Drilling, Stimulation and Production
Heterogeneity and Scaling
High Performance Computing: The Challenge of Harnessing HPC for Rock Mechanics
High Temperature and High Pressure Rock Testing
Nano/micro Geomechanical Testing: Its Applications and Implications
Rock Physics and Geophysics
Transport and Coupled Processes in Fractures and Along Interfaces
Acoustic Emissions
Review of Software used for Rock Mechanics
Pore-scale Imaging and Processes
Rock Mechanics and Sustainable Development
Thermal, Hydrological, Mechanical, Chemical and Biological Influences upon Rock
Uncertainty Quantification and Parameter Estimation in Geomechanics
Other Interdisciplinary

News Briefs

Bernard Amadei Appointed U.S. Science Envoy

ARMA member **Bernard Amadei** has the distinction of being appointed Science Envoy by the U.S. State Department. According to the Department's announcement, these "preeminent scientists seek to deepen existing ties, foster new relationships with foreign counterparts and discuss potential areas of collaboration that will help address global challenges and realize shared goals. The Envoys travel in their capacity as private citizens, advising the White House, the Department of State, and the U.S. Scientific community about the insights they gain from their travels and interactions."

Dr. Amadei is Professor of Civil Engineering at the University of Colorado, Boulder; his main research interests have been focused on rock mechanics and engineering geology. He is the founding president of Engineers Without Borders and is a member of the U.S. National Academy of Engineering. He has served as a former President of ARMA and is currently an ARMA Fellow.

ARMA President Elected the Einstein Chair Professor of the Chinese Academy of Sciences

The Chinese Academy of Sciences annually selects 20 top world scientists across all science and technology fields, in recognition of distinction in their respective disciplines and for their contributions to advancement of science on a global basis. **Mark Zoback**, current President of ARMA and an ARMA Fellow, was the only nominee from the United States to receive this honor, in recognition of his work in rock mechanics and geoengineering.

ARMA Member Receives Honor

Submitted by Dick Goodman

Gen-Hua Shi was one of ten honorees named to the "Cambridge List of Most Distinguished Chinese People." He was cited for his work in "developing and furthering methodology for the analysis of jointed rocks used for the design and rehabilitation of surface and underground excavation throughout the world, as creator of numerical models and new mathematical formulations respecting the kinematics of discontinuities and discontinuous solids in general." He was involved in work related to ISRM's Commission on Discontinuous Deformation Analysis.

Announcing Publication of "Rockfall: Characterization and Control"

Robert L. Schuster, ARMA member and co-editor A. Keith Turner announced the publication of **"Rockfall: Characterization and Control"** in Fall 2012. The volume, developed over five years by a Transportation Research Board task force, presents material authored by a dozen internationally recognized rockfall experts. It addresses the state of knowledge about rockfall, the available procedures for rockfall investigation, and the regulatory and economic climates affecting rockfall investigations and corrective actions. This material is timely not only because of hazards from aging transportation infrastructure but also because of enhanced knowledge of the rock mechanics and geoengineering that continues to build understanding about the prevention and treatment of rockfall events. (Further information can be obtained by email to TRBSales@nas.edu.)

In Memoriam

Obituary: Howard Pincus

Howard Jonah Pincus, one of the Founders of ARMA, died peacefully on 17 October, 2012 at age 90. He was a first-generation American born at his aunt`s home in Brooklyn, New York in 1922. His father, Otto Max Pincus (originally Pincu), who had emigrated from Romania in 1901, was a cloth cutter in New York`s garment district; his mother, Gertrude (nee Jankowsky), who had emigrated from Poland in 1897, was a homemaker. Howard spoke often of his father`s stoic efforts to support his family throughout the Depression and of his mother`s kindness and love of poetry.

As a child, Howard and his family moved to the Bronx, where he attended Public School 28. He graduated from DeWitt Clinton High School in the Bronx in 1938 at age 15. Howard earned a B.S. in Mathematics at the City College of New York, graduating as a Phi Beta Kappa in June, 1942. Howard then enlisted in the U.S. Army, earning the rank of First Lieutenant and commanding a combat engineering group in the Philippines.

Returning to New York City after the war, Howard completed masters and doctoral degrees in Geology at Columbia University, where he also was elected to the Sigma Xi scientific research society.

After Columbia, Howard`s professional career included positions from instructor to full professor and chairman of the Department of Geology at Ohio State University (1949-1967); geology research supervisor at the U.S. Bureau of Mines in Minneapolis, MN (1967-1968); full professor of geology and civil engineering and dean of the College of Letters and Sciences at the University of Wisconsin-Milwaukee (1968-1987) -- where he also received the university`s first Alumni Award for Teaching Excellence; and consultant in geology, rock mechanics, tunneling, and energy storage in rocks in San Diego, California (1987-2009).

During his professional career Howard published more than 100 articles, papers in technical journals, and chapters in scientific and educational books, as well as serving with the National Science Foundation, National Academy of Engineering, National Academy of Sciences, International Association of Engineering Geology, and as a member of the American Society for Testing and Materials, which awarded him both Merit and Frank W. Reinhart Awards.

Howard is survived by his loving wife of 59 years, Maud, children Glenn and Philip, and four grandchildren.

Obituary: Francois Heuze

Francois Heuze, an ARMA Fellow who served on the Board of ARMA and as its President (2002-2005), died at his home after a long untreatable illness. He was also the Co-chair of the 23rd U.S. Symposium on Rock Mechanics. He has received the Applied Rock Mechanics and Case History Awards from ARMA and from the U.S. National Committee for Rock Mechanics. He is survived by his wife Michele, his daughter and son, four grandchildren and his brother, Louis.

With an expertise in rock mechanics and geological engineering, he was a leader of Lawrence Livermore National Laboratory's geotechnical programs. He was responsible for numerous projects in the areas of mine design, tunnel vulnerability, slope stability, rock and joint testing, rock fracture mechanics, underground nuclear waste storage, explosion effects, cratering, projectile penetration, hydrofracturing, mine seismicity, drilling, soil dynamics, and earthquake effects.

Francois was born in Algeria, and moved to California when he was 25. He received a Masters in Mining Engineering from National School of Mines (France), followed in 1970 by his PhD. in Civil Engineering from the University of California, Berkeley.

He was not only active, but honored, in his professional and academics pursuits. In addition to his service for ARMA, he served as Vice-President North America, International Society for Rock Mechanics, 2003-2007. He served on the National Research Council's Geotechnical Board and Board on Energy and Environmental Sciences from 1988-1997. Since 1974, he taught numerous short courses on rock mechanics and geoengineering. He had over 170 publications and was a Fellow of the American Society of Civil Engineers.

He enjoyed flying airplanes, playing tennis and traveling the world. His last years were spent enjoying time with family.

In Tribute of Francois Heuze

(Editor's note: Upon learning of the death of ARMA Fellow Francois Heuze, Dick Goodman submitted the following personal tribute)

Francois Heuze was one of my earliest graduate students at Berkeley. Francois' doctoral research was an early application of applied rock mechanics for optimizing mining design. Our field laboratory was Riverside Cement Company's large underground marble mine. The research included instrumentation of one of the first mine-by experiments of which I am aware. It involved very early trials of the finite element analysis, coupled to strain measurements, for optimization of mining procedures in 3- dimensional caverns in discontinuous rock. Francois continued at the university as a post doc for a while to help manage research projects, which eventually included a sizeable faculty group under the leadership of Professor Jim Mitchell, who was studying presumed or simulated lunar soil properties.

Francois joined me on consulting projects on several occasions, including joint overcoring measurements of the in situ state of stress in the abutment of Ruedi Dam, Colorado, in support of the excavation contractor's claims. This involved drilling overcores in the cold of a Colorado winter on a mountain slope during an "artificial" snowstorm caused by the spray of leaking drill water, with the analysis complicated by snow falling on us and our notebooks. On another job, we produced a comprehensive stereographic projection analysis of potential rock wedges in the spillway excavation for the ill-fated Auburn arch dam project.

Subsequently, he joined the faculty of the University of Colorado, Boulder before finally settling down at Livermore. His work there, among other subjects, produced rock mechanics studies associated with underground nuclear testing (including another mine-by experiment). While at Livermore, Francois continued to teach courses at U.C. Davis. He also consulted on various projects including an analysis of seismic hazards to the buildings of the University of California campus in Berkeley.

Francois became a co-worker and a close friend. Michelle and Francois Heuze were wed at a ceremony in my garden. We interacted as organizers of conferences and seminars, and co-taught courses held at various universities and at ARMA Conferences. As his illness became apparent, Francois responded in his accustomed manner with stubborn energy and determination - - never consciously yielding. He was a tough, courageous fighter -- all his life -- and we are much in his debt.