EXXONMOBIL
ENERGY, PROCESS & UTILITIES

Challenge:

- With a decades-long working relationship of building their in-house simulation capabilities with the support of SIMULIA technologies, ExxonMobil wanted to further strengthen their simulation toolkit to enable them to better address the many challenges involved in the subsurface extraction of shale gas.

Solution:

- SIMULIA worked closely with Exxon to develop state-of-the-art general-purpose material models, finite-element technology, and computational procedures including fluid dynamics (CFD) and particle flow dynamics (PFD)—aimed at identifying solutions that could be applied in the field.

Benefits:

- This collaborative effort between ExxonMobil and SIMULIA led to fundamental enhancements to the power of simulation to address key drilling, completion and production challenges. SIMULIA's advanced simulation technologies and 3D visualization are playing an increasingly vital role in the success of ExxonMobil and the energy industry at large.
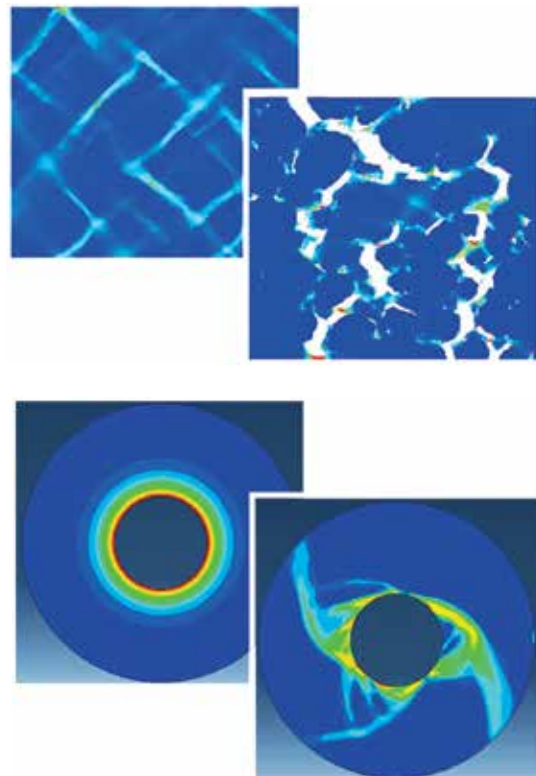
extraction of shale gas. This collaboration would concentrate on the development of state-of-the-art general purpose material models, finite element technology, and computational procedures aimed at identifying working solutions to such challenges.

The team consisted of senior engineers at ExxonMobil partnering directly with SIMULIA personnel. In particular, Kevin Searles played a significant role in establishing the key technical underpinnings and advising the joint development collaborative steering team since its inception. Also important has been the sustained ExxonMobil management leadership of Bill Kline, Jason Burdette and Erika Biediger over the duration of the joint project. (See sidebars for profiles of contributors.)

At this year's SCC in Berlin, Dale returned to provide a fascinating in-depth look at just how far the joint partnership with SIMULIA has progressed and how sophisticated the resulting capabilities have become over the last five years. In addition to the SCC, the ExxonMobil team is rolling these technologies out at oil and gas technical events as well.

"This collaborative effort between ExxonMobil and SIMULIA has led to the development of fundamental improvements in simulation to address key drilling, completion and production challenges in the oil and gas industry," said Dale. "Advanced

In just the last decade, the outlook for clean-burning natural gas as a major contributor to meeting global demand for energy has dramatically changed. In 2000, shale gas represented just one percent of natural gas supplies in the U.S., for example. Today that figure is 30 percent and rising.

Why? Because innovative solutions, developed from technologies long used by oil and gas companies, are now being applied successfully to unconventional resources like shale rock as well. This subsurface work is filled with all kinds of technical challenges that require detailed insights and understanding of the complex physics involved. One major company taking a leadership role in the use of simulation to power such innovation is ExxonMobil.

ExxonMobil was an early licensee (in the late 1970s) of Abaqus software in the energy sector. The relationship was more than simply commercial—ExxonMobil was also an early collaborator with SIMULIA on technology development to enable simulation of key energy-sector performance challenges. For example, collaboration with ExxonMobil led to the very first large sliding displacement capability in Abaqus. This technology was used to increase pressure and temperature capacity as well as reliability of threaded-pipe production tubulars and equipment.

Bruce Dale, Chief Subsurface Engineer for ExxonMobil, first described his company's three-plus decades' collaboration with SIMULIA and its predecessors during a keynote speech at the 2010 SIMULIA Community Conference. Shortly after that speech, his engineering team embarked on a new effort with SIMULIA to further strengthen simulation capabilities that would help address the many challenges involved in subsurface

(Top) Advanced finite element models and (Bottom) advanced constitutive models, co-developed between ExxonMobil and SIMULIA.
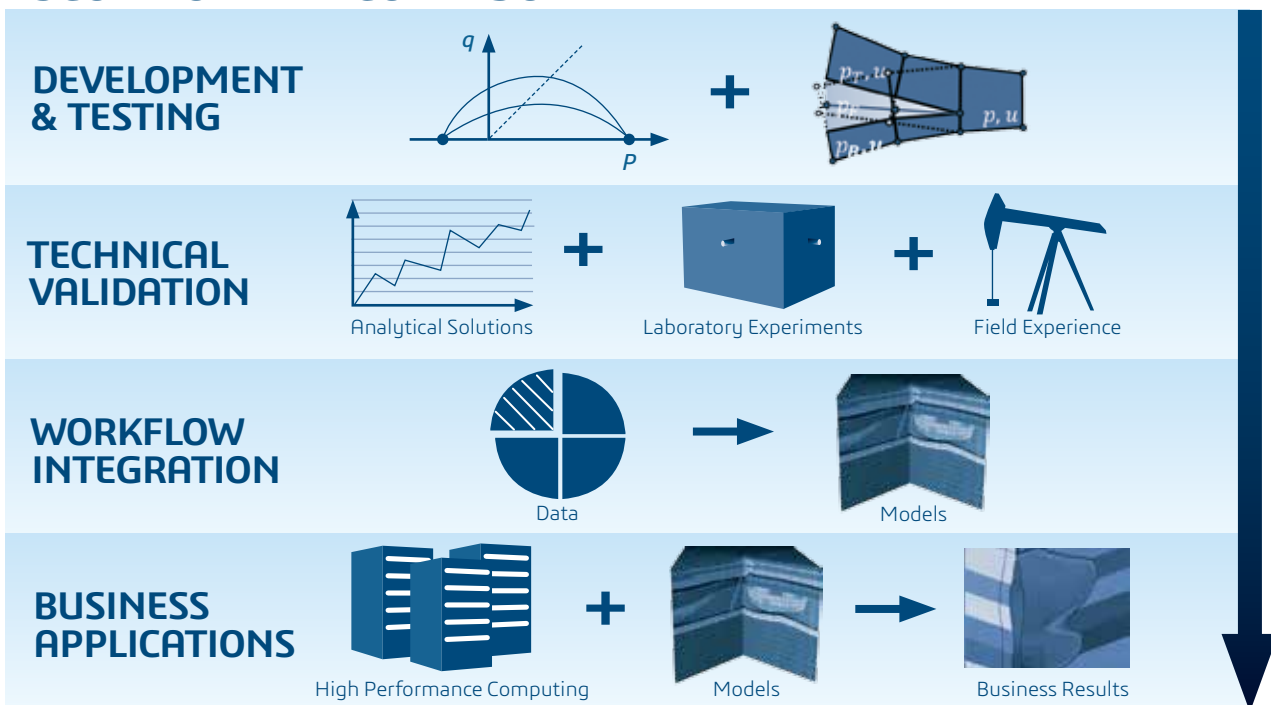
Jing Ning

Jing Ning, a senior research engineer, finished her Ph.D. in mechanical engineering at Cornell University and joined ExxonMobil Upstream Research Company in 2013. She is currently working on drill cuttings, re-injection, and hydraulic fracture modeling of various aspects of water injection. "It has been a great experience working with SIMULIA engineers on this joint development agreement," she says. Pablo Sanz, co-author of the SCC 2015 paper, explains how "Simulation has made our work more productive in that more accurate results can be delivered to the business for a small increase in time." In their SCC 2015 paper, Experimental Validation of Simulation Capabilities for Hydraulic Fractures Propagating in a Porous Medium, Ning, Sanz and teammates found good agreement between Abaqus simulation and experimental results for two benchmark studies of fluid-driven fractures. "Solving these challenges is critical to the business values we are going after," says Sanz.

Jorge Garzon and Matias Zielonka

Jorge Garzon, a senior research engineer in the well performance section of the ExxonMobil Upstream Research Company, has a Ph.D. in civil engineering from the University of Illinois. He works on the creation of 3D geomechanical models for analyzing phenomena such as slippage between faults and wellbore and casing integrity. "These recently developed capabilities combine the sophisticated physics of "research codes" with the ability to run "fast enough" models for full-scale commercial applications," he says. "This helps us predict the geometry of hydraulic fractures and the pore pressure changes resulting from oil and gas operations." Jorge and **Matias Zielonka** wrote Advanced Fracture Modeling for Cuttings Re-injection for the 2015 SCC. Matias is a senior engineering specialist in the surveillance and well simulation function at the Company. He holds a Ph.D. degree in aeronautical engineering and applied computation from Caltech. "These fully coupled capabilities we've developed with SIMULIA allow us to test scenarios that cannot be reproduced in the lab and to apply what we learn to our models with great accuracy," says Matias.

SCOPE OF THE COLLABORATIVE INITIATIVE

DEVELOPMENT & TESTING

TECHNICAL VALIDATION

Analytical Solutions   Laboratory Experiments   Field Experience

WORKFLOW INTEGRATION

Data   Models

BUSINESS APPLICATIONS

High Performance Computing   Models   Business Results

DEVELOPMENT TO BUSINESS APPLICATIONS

Nikolay M. Kostov

Research engineer **Nikolay M. Kostov** joined ExxonMobil's Upstream Research Company after finishing his Ph.D. in mechanical engineering at Rice University. He is now using Abaqus for modeling drilling-induced fractures and wellbore integrity prediction. The paper he and colleagues submitted for the 2015 SCC, <u>Dynamic Hydraulic Fracture Modeling for Wellbore Integrity Prediction in a Porous Medium</u>, describes the unique fracture-modeling capabilities in Abaqus that use advanced CZM (Cohesive Zone Method) elements. "The automated workflow allows a much better use of my time," he says. The tools he and his team have developed together with SIMULIA have increased their confidence in predicting scenarios, he notes: "Some properties that aren't well known in advance can nevertheless be estimated with empirical models. We can also specify ranges of values instead of individual ones to cover areas of uncertainty."

Ganesh Dasari

Ganesh Dasari is the technical team lead for well operability and subsurface geomechanics in ExxonMobil's Upstream Research Company. Ganesh joined the Company in 2003 after finishing his Ph.D. in civil engineering at Cambridge University. Describing his group's work in their 2015 SCC paper, <u>Simulation of Hydraulic Fracturing of Unconsolidated Sands using Fully Coupled Poro-Elastoplatic Models</u>, Dasari says, "Fracturing in unconsolidated sands involves complex failure mechanisms. Our realistic material model is the key to capturing this behavior and optimizing fracturing design."

These advanced Abaqus models showed that fracturing in sands was dominated by shear failure as opposed to the type of tensile failure seen in hard rock. "We were pleased that our model captured this key feature," he said. "These encouraging results allow us to apply simulation to field scale injection problems at increased length and time."

simulation technologies and 3D visualization play an increasingly vital role in the success of the energy industry and include such modeling capabilities as finite element analysis (FEA), computational fluid dynamics (CFD) and particle flow dynamics (PFD)."

Dale has been a participant in this effort since the start of his career with Exxon in the 1980s, beginning with research and development supporting the drilling business and moving into management and leadership roles over time. He is a champion of new "game changing" technologies; and fostered innovation, creativity and excellence throughout his 34-year professional career. "I had an opportunity early on to work with Abaqus, part of the Dassault Systèmes SIMULIA suite of tools, and that was a great way to apply advanced technology to simulate those things which, in the past, we'd only been able to test in the laboratory or in the field," he said, in an interview after his 2015 talk.

"I've always had a natural curiosity, wanting to figure out the 'why' of things—and one thing that led to was the early use of technology from its infancy." [Other things his curiosity has led to include 20 patents issued for his ideas, and 40 or so more in progress!] As the simulation capabilities in Abaqus have expanded, Dale said, "I've been fortunate to work with a number of very talented and bright people. When we collaborate using these tools, the ideas just begin to flow."

Employing simulation at ExxonMobil has increased the company's competitiveness, Dale said. "The power of being able to connect the dots is one you're never able to do fully

Additional CONTRIBUTORS

Bill Kline is Manager of the Drilling and Subsurface Function of ExxonMobil Upstream Research Company. He holds a PhD in Chemical Engineering from the University of Michigan. Bill is a co-founder of Pumps & Pipes, an international symposium series that brings together oil & gas, medical aerospace, and other professionals to explore common interests and opportunities for collaboration.

Kevin H. Searles, Ph.D., is Geomechanics Advisor for ExxonMobil Upstream Research Company in Houston, Texas, and Technical Lead of new hydraulic fracture modeling technologies co-developed in Abaqus. Kevin has spent the past 15 years working on reservoir compaction, thermal EOR, geothermal heat recovery, hydraulic fracturing, and cuttings/water disposal applications worldwide, including simulation. He has numerous patents on methods and processes for multi-scale geomechanics analysis, fluid injection control, and integration of geomechanics and seismic monitoring.

Erika A.O. Biediger is Well Performance Manager for ExxonMobil Upstream Research Company in Houston, Texas. Erika received a Ph.D. degree in Mechanical Engineering from Georgia Institute of Technology and has six U.S. patents. Erika currently manages the R&D technical team focusing on the new Abaqus fracture modeling technologies developed in conjunction with SIMULIA.

Jason A. Burdette is U.S. Drill Team Engineering Manager for ExxonMobil Development Company in Houston, Texas. Jason joined ExxonMobil in 2001 after receiving an MS degree in Engineering Mechanics from Virginia Tech. Prior to his current assignment, Jason managed the R&D technical team working on new Abaqus fracture modeling technologies developed in conjunction with SIMULIA.

Pablo F. Sanz is Well Injectibility and Induced Seismicity Team Lead at ExxonMobil Upstream Research Company. Pablo joined ExxonMobil in 2008 after finishing PhD in Computational Geomechanics from Stanford University. His research interests lie in the area of computational geomechanics and fracturing with applications to drilling, subsurface engineering, and induced seismicity problems.

Additional contributors at ExxonMobil Upstream Research Company in Houston, Texas:

Scott R. Buechler is Well Production and Well Stimulation Team Lead.

Michael S. Chelf is the Well Construction Section Manager.

Ranojoy D. Duffadar is an Engineering Specialist in the Drilling and Subsurface function.

Gilbert C. Kao is an Engineering Associate.

Sandeep Kumar is a research engineer in the Well Performance section.

Fuping Zhou is Senior Engineering Specialist.

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in the laboratory because of cost, size and time," he said. "In the past, the time available often wouldn't fit within the period where decisions had to be made.

"The visualization now possible with simulation allows you to do the interpretation—to spot either opportunities or flaws—a lot earlier. This impacts and affects the here and now much more so than ever before. So in the upstream business, visualization is a great aid, able to bring folks together with disparate types of information analyses and data to solve some very tough challenges."

In his 2015 SCC address, Dale discussed his company's commitment to developing natural gas resources in a safe and reliable manner. ExxonMobil has developed best management practices to increase efficiencies while reducing the overall environmental footprint, he said. This includes protecting local ground water resources, working closely with communities and government and promoting transparency and efficient regulation.

Dale explained that extracting natural gas from shale rock involves the complex physics of

- Drilling (creating a useable borehole)
- Completion (providing a conduit from the reservoir to the surface)

- Stimulation (enhancing the connectivity of the well to the reservoir rock face)

- Production (managing the flow of reservoir fluids through the well, treating facilities and piping systems)

- and Waste Disposal (re-injection of untreatable fluids safely back into deep subsurface horizons)

In order to accurately model the critical factors that can impact the success of these many phases of extraction, ExxonMobil and SIMULIA have now developed a fully coupled formulation for fluid-driven (hydraulic) fracture growth using two advanced finite element methods: a cohesive zone method (CZM) in which fracture trajectory is confined to a plane; and an extended finite element method (XFEM) in which fracture trajectory is entirely solution dependent.

In addition to these advanced finite element methods, advanced constitutive models were also implemented in Abaqus to account for the inelastic deformation associated with the types of unique, complex failure mechanisms seen in soft rock.

In all cases, methodologies have been rigorously validated over a wide range of rock and fluid properties as well as fluid-loss conditions, both against semi-analytical solutions and against lab-scale experimental results.

ExxonMobil has developed unique experimental capabilities in-house, then worked with SIMULIA to create 2D and 3D models of many different aspects of controlled hydraulic fracturing in rocks. "By incorporating physically measured input parameters and representing the full physics, not simply 'tuning' the models to achieve the desired results, we are confident in our validations of these newly co-developed numerical capabilities in Abaqus," Dale said.

These recently developed simulation capabilities are supporting ExxonMobil's hydraulic fracturing business in many ways, Dale pointed out. "Avoiding drilling problems cuts costs," he said. "Managing drilling risk means not letting small problems become big ones. Advanced 3D simulations enhance our ability to anticipate drilling-related issues—such as instability in shales or lost returns in sands—and mitigate risks. Simulation also helps us develop innovative recovery schemes to make production more economical."

"The fruits of our collaborative partnership with SIMULIA are many," Dale concluded. "In the decades ahead, the world will need to expand energy supplies in a way that is safe, secure, affordable and environmentally responsible. 3D simulation powers innovative solutions by building on the fundamentals to deliver energy in the 21st century."

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