Managed Pressure Drilling

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The mission of the IADC Technical Publications Committee is to publish a comprehensive, practical, and readily understandable series of peer-reviewed books on the petroleum drilling industry known as the *Gulf Drilling Series* in order to educate and guide industry personnel at all levels.

This book has been peer reviewed in accordance with this mission by:

Gavin Humphries, Stena Drilling
Ken Malloy, Stress Engineering
Bill Maurer, retired, Maurer Engineering
Jay Smith, Viking Engineering

Preface

Since the early 1970s, a loosely organized technical group of oilfield personnel from both operators and service companies has made a consistent effort to write and publish technical information. The group, initiated by Dr. Leon Robinson, then of EPR, started by trying to establish some logical rules for shale shaker screens and progressed to the general subject of solid control for drilling fluids.

In 2006, the publisher of Gulf Publishing Company approached the group and asked if it would be interested in developing a series of technical books that detailed modern drilling technology. With the "big crew change" in progress, the industry was in danger of losing some of its basic hard and expensively learned technology. After some discussion, the renamed IADC Technical Publications Committee agreed to undertake the project: some 10 or 15 technical books, with some organizational and administrative help from the IADC and publishing rules and marketing efforts by Gulf Publishing Company. The basic premise of each book was that it was to briefly review the past technology and present the present technology and practice in such a way as to be useful to the operating engineer, the rig supervisor, and students of the subject. The subject matter was to be limited to the technical subject involved, with enough discussion of ancillary material that the reader understood the basics of the subject. Other books in the series would cover those and other technical subjects.

A list of technical subjects was developed, along with some general presentation rules; and authors and technical editors were solicited. Each book was to be the responsibility of a senior author, who would arrange for additional help from other general or chapter authors.

This is the second book of the series. Managed pressure drilling (MPD) is a method of drilling in a balanced or overbalanced state

while threading the pressure limit between pore pressure or well-bore stability and fracture pressure. MPD seeks to avoid a well kick.

The precise technologies of MPD were first put in practice within the five to seven years prior to the publication of this book. The general information about MPD is well documented in SPE technical papers and in the IADC Underbalance and Managed Pressure Drilling Workshops. Actual operational procedures about the effect of such items as pump-rate changes, well-bore ballooning, pipe movement, and trips are less well documented. These items are the critical element of actual operations, and the knowledge is resident only in the people who have actually done it. Since no one has seen it all and done it all at this early stage in managed pressure operations, it is evident that to present and publish that information, the principal author would have to go to the people with the most field experience or special abilities.

We sought out the people most knowledgeable and experienced in the various subjects as chapter authors. Since this is new technology, many of those individuals are with the service organization marketing the technology or associated equipment. Each chapter retains some special views of the service company and often the passionate views of the chapter author. There is also a significant amount of overlap in all the chapters. Field operations do not take place in a vacuum, and in actual practice, most of the techniques tend to approach a common point. The principal authors attempted to homogenize some of the styles and illustrations (and commercial comment) without taking out the special flavor of the most knowledgeable writers. Despite, or perhaps because of, their parochial views, we are all indebted to the drilling specialists who took the time to write and advise on the content of this book. It would not be possible to present the insight into the various operations without them. I would like to give special recognition and thanks to Don Hannegan of Weatherford, who spent an inordinate amount of time explaining many of the issues about which I was unclear. Although he was not listed as an author, his influence in the book was not insignificant. I would also like to thank Ken Malloy of Mohr Engineering for critical comments organization that helped change the outlook of the entire book.

Words do not always portray exactly the same idea to all people. But all of us have done our best to make the information clear and straightforward.

The book has been technically reviewed by independent, knowledgeable individuals not associated with any of the authors or the book group. The technical reviewers have generally been members of the IADC Underbalance and Managed Pressure Drilling Committee, who worked on there own time to help us. We are indebted to them for pointing out errors in clarity and technology. However, the reviewers of this book do not represent the IADC Underbalance Operations and Managed Pressure Drilling Committee, and the committee has not reviewed this book.

—Bill Rehm

Contributors

Jim Brugman is chief engineer of National Oilwell Varco's Pressure Control Group in Houston. He has led the new product development efforts for this group (formerly, the Shaffer division of Varco International) since January 1994 and was responsible for new product R&D engineering since that time. Prior to that, he spent 21 years developing new products for Varco Oil Tools and Varco Drilling Systems in Orange, California, where he was responsible for the development of the Iron Roughneck, Top Drive Drilling System, Pipe Handling Machine (PHM), Star Racker, and the Pipe Transfer System. He received a BSE degree in Mechanics and Structures from UCLA in 1975.

Erdem Catak is a project engineer for Secure Drilling. Currently, he is responsible for assisting the development and introduction of Secure (managed pressure drilling) in the field, supervising field applications, preparing training materials, teaching rig crews and drilling engineers how Secure works, reviewing potential well candidates with clients, and promoting the method in conferences, exhibitions, and meetings. Before joining Secure Drilling, Catak worked for the Louisiana State University Petroleum Engineering Research and Technology Transfer Laboratory as a coinstructor and trained rig personnel on advanced hands-on well control methods. He taught drilling fluids and well control classes at LSU, where he earned his MS degree in Petroleum Engineering. He also taught classes at Istanbul Technical University, where he graduated with an honors degree in Petroleum and Natural Gas Engineering. Catak is a member of SPE, IADC, and AADE, and a lifetime member of Pi

Epsilon Tau, the Petroleum Engineering Honor Society. He is an advisory board member of the Well Control Gulf of Mexico. Several technical papers and articles by him have been published by SPE, IADC, AADE, and various magazines. He can be contacted at ecatak@securedrilling.com.

John Cohen worked in research and development in the oil industry since his graduation from the Colorado School Mines in Golden, Colorado. His degree in Mineral Engineering Physics has given him a unique view and allowed him to work on a variety of projects over the past 35 years. Cohen has significant experience in developing and improving down-hole tools, including roller cone and PDC drill bits, turbodrills, mud motors, turbine generators, MWD tools, rig instrumentation, and rotary steerable tools. He has also worked on subsea equipment, including riser design, collet connectors, and subsea pumping systems. Cohen was director of a drilling laboratory, where he developed methods and apparatus for testing oilfield equipment, down-hole tools, and drilling concepts. Included among these was the testing of fluids for a unique method of dual-gradient drilling. This interest in new technology and dual-gradient drilling continues, with work on subsea pumps and concepts for dual-gradient and riserless drilling.

Brandee Elieff is a drilling engineer in the U.S. drilling group at ExxonMobil Development Company in Houston. She earned a BS degree in Petroleum Engineering from Texas A&M University in 2004. She further earned an MS degree in Petroleum Engineering from Texas A&M University with a Drilling Engineering focus and an MS degree in Petroleum Economics and Management from the Ecole Nationale Supérieure du Pétrole et des Moteurs (Institut Française du Pétrole) in 2006. She has been working for ExxonMobil Development Company since 2006, where she has worked offshore in West Africa and on land in the United States.

Paul Fredericks works for At Balance in Houston and has 30 years of international and domestic oilfield experience, ranging from

open- and cased-hole wireline, measurement, and logging while drilling and managed pressure drilling. His career spans field operations, log analysis, technical support, operations and product line management, and marketing. Fredericks joined At Balance as director of marketing in 2005 and directs all activities related to marketing, advertising, sales support, and communications for the company and its products and services. His technical articles have been published and presented for various professional organizations including the SPE, IADC, and SPWLA. He graduated from the University of Mississippi with degrees in Geology, Physics, and Mathematics.

Arash Haghshenas is a PhD candidate at Texas A&M University. He holds a BS degree from Petroleum University of Technology in Iran and MS degree from the University of Louisiana at Lafayette in Petroleum Engineering. Currently, he is involved in managed pressure drilling, underbalanced drilling, and well control projects at Texas A&M University. He also is member of the IADC Book Publishing Committee.

Jim Hughes has 28 years' experience in all phases of the upstream oil and gas business. His first 9 years were devoted to drilling and production operations, prospect generation, and acquisitions under the tutelage of David K. Davies, his first employer and mentor, who taught him extensive completion design practice using formation-damage prevention techniques. Over the next 10 years, Hughes developed and utilized short radius, multilateral underbalanced horizontal drilling (UBHD) technology as a primary completion and recompletion method to improve productivity. After several years of research and development and purchase of his own drilling rig, in 1991, Hughes, using an air hammer, drilled the first horizontal lateral well from a short-radius (25-ft) curve. Over the next 3 years, he spent most of his time evaluating reservoirs for the recovery of bypassed reserves, using UBHD technology as a completion technique. During this time, he was in Oman as part of the first independent technical team invited to recommend well construction methods and evaluate indigenous oilfields for redevelopment, using

UBHD technology as a completion technique. Hughes has devoted most of the last 10 years to patenting new technologies related to UBHD, including a new short-radius self-steering bottom-hole assembly, an artificial lift-while-drilling process for managed pressure drilling, and smart drill pipe. He currently holds 12 patents related to UBHD. He is a graduate of the University of Missouri with a BS degree in Geology.

George Medley is the executive vice-president of Signa Engineering Corporation and has over 30 years in oil and gas operations and R&D. Along with extensive drilling, completions, and operations management, he has managed R&D projects for the U.S. Department of Energy, the Gas Research Institute, and the Drilling Engineering Association. He developed multiple training courses in unconventional drilling techniques. Medley holds a BS degree in Civil Engineering from Texas A&M University and received one of five regional SPE International Drilling and Completion Engineer awards for 2005–2006.

Dennis Moore received a BS degree in Petroleum Engineering from Texas A&M University. Since then, he has worked for major oil companies, independent operators, and consulting engineering companies, serving in a variety of drilling, production, and reservoir engineering positions worldwide. These jobs provided him with a diversity of both engineering design and well site supervision experience on HPHT, horizontal, underbalanced, and managed pressure projects, including drilling with casing and with coiled tubing. He has 30 years' experience in the oilfield, authored or coauthored several articles on underbalanced and managed pressure drilling, and is a registered professional engineer in Texas. He currently is the vice-president of international managed pressure drilling with New Tech Engineering, based in Houston, and can be reached via email at dennisdmoore@yahoo.com or by phone at 281-687-8584.

Sagar Nauduri is a PhD candidate in the department of Petroleum Engineering at Texas A&M University. He received his master's de-

gree from Robert Gordon University, Aberdeen, UK, and his bachelor's degree from Andhra University, India. He is involved in the managed pressure drilling research project at Texas A&M University.

Amir Saman Paknejad is a PhD candidate at Texas A&M University. He holds a BS degree from the Petroleum University of Technology in Iran and an MS degree from the Texas A&M University in Petroleum Engineering. Currently, he is involved in managed pressure drilling, underbalanced drilling, and well-control projects at Texas A&M University. He also is a member of the IADC Book Publishing Committee.

Bill Rehm, the principal author for *Managed Pressure Drilling*, is a drilling consultant in and the author of *Practical Underbalanced Drilling and Workover*. He has some 30 years' experience in underbalanced drilling, starting with some of the early foam drilling on the AEC site in Nevada and foam workover in California, up though experiences in Canada and present-day operations with gaseated fluids in such diverse areas as the Austin Chalk, Illinois, and California. In his broad experience, he was an early contributor to well-control technology and chief engineer for a service company when drilling chokes were first being introduced as a method of controlling well pressure. As general manager of a directional drilling company, in the early days of learning in the Austin Chalk, he participated in the development of many of the ideas that lead to today's underbalanced and managed pressure drilling. At present, he is active as a consultant in coal-bed methane and is actively engaged in corrosion control and foam workover in Wyoming. He holds several patents and has written more than 50 publications on the subjects of well pressures, well control, horizontal drilling, and underbalanced drilling. He can be reached at rehm@earthlink.net.

Jerome Schubert has a BS (1978), MEng (1995), and PhD (1999) all in Petroleum Engineering from Texas A&M University and is currently an assistant professor and Larry Cress Faculty Fellow in the Harold Vance Department of Petroleum Engineering at Texas

A&M University. Schubert has worked as a drilling engineer for over eight years with Pennzoil Company and Enron Oil and Gas, over four years as a well-control instructor with the University of Houston/Victoria Petroleum Training Institute, and as a faculty member at Texas A&M University since 1994. At Texas A&M University, he is involved in teaching graduate and undergraduate drilling courses. Related research activities with which Schubert has been involved include kick detection, well kill procedures, shallow-water flows, underbalanced drilling, managed pressure drilling, evaluation of the conductor casing setting depth in shallow water, risk assessment of surface BOPs and high-pressure risers on MODUS in the Gulf of Mexico, and development of well-control procedures for dual-gradient drilling. He also serves on the IADC Training and Well Control Committees and the IADC WellCAP Review Panel. Schubert is a member of Pi Epsilon Tau and Sigma Xi and was on the Subsea Mudlift JIP Well Control Team. He is author or coauthor of over 30 conference and journal papers as well as the holder of three dual-gradient drilling patents.

Roger Stave, currently president and chief technical officer of AGR Subsea, Inc., has a vast breadth of oil and gas drilling and design experience, covering a career of over 30 years. He worked with a major operating company in the North Sea, managing projects and supervising technology developments for a variety of new projects, and performed many high-profile consulting roles. He most recently has been instrumental in developing the Riserless Mud Recovery™ (RMR) system, dual-gradient drilling techniques, and other enabling technology for deepwater drilling operations, all of which are operational around the world, with consistent success. His contribution to many of the major offshore projects in the Norwegian sector of the North Sea during a very productive period of new production and platform design, construction and installation, and development of gas injection, modifications, and new technologies primarily for offshore deployment, enables him to combine an innovative and commercially successful contribution to the petro-

leum industry. He has presented papers around the world and is the originator of six patents.

Rod Vogel has over 20 years of diversified oilfield experience, varying from oil company reservoir engineering to service company operations management. Vogel began his career with Marathon Oil Company in the United States, where he held various positions in reservoir, operations, and drilling and also specialized in stimulation fluids and horizontal drilling. He participated in engineering the production turnaround of the 4-billion barrel Yates field in the early 1990s and the implementation of Marathon's short-radius horizontal drilling program. In 1993, he left Marathon to found and manage a horizontal drilling company, specializing in short-radius and underbalanced drilling. Vogel joined a Weatherford company in Aberdeen, Scotland, in 1997 and held several international positions, managing underbalanced drilling operations and projects across the eastern hemisphere. He joined National Oilwell Varco in 2003 and is presently director of global rental operations, based in Houston. Products and services in his group include the CCS (continuous circulation system), PCWD operations (Shaffer's rotating annular BOP), and rentals of other rig equipment including top drives and iron roughnecks. He holds a BS in Petroleum Engineering from Pennsylvania State University and an MBA from the University of Texas.

List of Abbreviations

APL	Annular pressure loss
BHA	Bottom-hole assembly
BHP	Bottom-hole pressure
BML	Below mud line
BOP	Blow-out preventer
BPD	Balanced pressure drilling
CBHP	Constant bottom-hole pressure
CBP	Constant bottom-hole pressure
CCS™	Constant circulating system
CIV	Casing isolation valve
D	Depth
D	Diameter
DAPC™	Dynamic annular pressure control
DDV™	Drilling down-hole deployment valve
DG	Dual gradient
DGD	Dual-gradient drilling
d_b	Diameter of the hole
d_p	Diameter of the (drill) pipe
DSE	Dual-sided elevator
DSV	Drill-string valve (subsea); see HCV
ECD	Equivalent circulating density
ECD-RT™	ECD reduction tool
EMD	Equivalent mud weight (density)
FBP	Formation breakdown pressure
FCP	Final circulating pressure
FIT	Formation integrity test
FS	Formation stability pressure; see P_{wbs}
H	Height of a column of mud or water

HAZID	Hazardous conditions identification
HAZOP	Hazardous operations plan
HCV	Hydraulic control valve; see DSV (subsea)
HPHT	High temperature, high pressure
HPU	Hydraulic power unit
HMI	Human/machine interface
IADC	International Association of Drilling Contractors
ICP	Initial circulating pressure
ICU™	Intelligent control unit
JIP	Joint industry project
K	Consistency index (drilling fluids)
KRP	Kill-rate pressure
KWM	Kill-weight mud; see W_2
L	Length
LC	Lost circulation
LMRP	Lower marine riser package
LOT	Leak-off test
LWD	Logging while drilling
MCD	Mud cap drilling
MD	Measured depth
MDU	Mud diverter unit
MLP	Mud-lift pump
MPD	Manged pressure drilling
MW	Mud weight (density)
MWD	Measurement while drilling
N	Flow behavior index
NPD	Nonproductive time
N_{re}	Reynolds number
NRV	Nonreturn valve (check valve)
OBM	Oil-based mud
OMW	Original mud weight; see W_1
P	Pressure
P_{bp}	Surface back pressure
PCWD™	Pressure control while drilling
P_{ds}	Differential sticking pressure

P_f	Fracture pressure
P_{fg}	Fracture pressure
P_{lc}	Lost circulation pressure
PMCD	Pressurized mud cap drilling
P_p	Pore pressure
P_{po}	Pore pressure
PV	Plastic viscosity
P_{wbs}	Well-bore stability pressure; see FS
PWD™	Pressure while drilling
QTV™	Quick trip valve
R	Gas constant
$R_{600,}\, R_{300\ \text{etc.}}$	VG meter readings at 600 and 300 rpm
RBOP™	Rotating blow-out preventer
RCD	Rotating control device
RMR	Riserless mud recovery
ROV	Remote operating vehicle
SCM™	Suction control module
SFL	Sacrificial fluid
SG	Specific gravity
SICP	Shut-in casing pressure
SIDPP	Shut-in drill-pipe pressure
SMD	Subsea mud-lift drilling system
SRP	Slow-rate circulating pressure
T	Temperature
TDCT	Top-drive connection tool
TVD	(True) vertical depth
v	Velocity
v	Volume
W_1	Initial mud weight (density)
W_2	Final mud weight (density)
WBM	Water-based mud
WD	Water depth
YP	Yield point
Z	Gas Z factor
Δ	Change in function

ρ	Density of mud weight
ρ_m	Density of mud
ρ_w	Density of water
ρ	Stress
μ	Viscosity
μ_{app}	Plastic viscosity; see PV