

Appendix F – Guthrie et al. 2010; Nodal Analysis Team Report

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Nodal Analysis Estimates of Fluid Flow from the BP Macondo MC252 Well

Conducted for the Flow Rate Technical Group (FRTG)
of the National Incident Command

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Table of Contents

1.0	Executive Summary	5
2.0	Background.....	5
3.0	General Approach.....	7
3.1	Data	7
3.2	Computational Models.....	8
3.3	Time Periods with Different Flow Conditions.....	9
3.4	Conceptual Flow Models	10
4.0	Conclusions	11
4.1	Flow Dynamics in Well	11
4.2	Choice of Conceptual Flow Model	12
4.3	Consensus Flow Rates	12
4.4	Sensitivity Analysis for Key Parameters.....	17
4.4.1	Benchmark Case	17
4.4.2	Impact of Gas-Oil Ratio (GOR).....	19
4.4.3	Impact of Blowout Preventer (BOP).....	19
4.4.4	Impact of Bottom Hole Conditions	19
4.4.5	Impact of Roughness Parameter for Pipes	20
4.4.6	Impact of Riser + drill pipe.....	20
4.5	Assessment of Results from Reservoir Modeling Team.....	21
5.0	Team Bios.....	23
5.1	LANL—Los Alamos National Laboratory	23
5.2	LBNL—Lawrence Berkeley National Laboratory.....	23
5.3	LLNL—Lawrence Livermore National Laboratory	24
5.4	NETL—National Energy Technology Laboratory	25
5.5	PNNL—Pacific Northwest National Laboratory	26

List of Figures

Figure 1: Schematic Diagram of the System Evaluated by the Nodal-Analysis Team.....6

Figure 2: Inflow Performance Relationship at Simulation Day 158

Figure 3: Schematic Diagrams of Well-Flow Scenarios11

Figure 4: Summary of NIST Results for Pooled Estimates of Flow16

Figure 5: Inflow Performance Relationships from Reservoir Team Models21

List of Tables

Table 1: Comparison of Simulations Conducted for Different Modeling Periods and Flow Conditions10

Table 2: Summary of Flow Estimates for Various Time Periods13

Table 2a: Summary of Flow Estimates for Time Periods 3 and 5.....14

Table 3: Benchmarking Results18

Table 4: Results for Sensitivity Analysis around Benchmark Case.....18

Table 5: Percent Change for Flow Rate Going from Low End of Parameter Range to High End of Range18

1.0 Executive Summary

The Nodal-Analysis Team estimated flow rate for various time periods based on modeling by five different DOE national labs, each using different approaches.

The estimated flow rates¹ for two key time periods were:

- 40,000–91,000 STB/day (95% confidence interval) with a corresponding best estimate of 65,000 STB/day for the time period following partial closure of the BOP but prior to capping of the drill pipe (25 April – 5 May)
- 35,000–106,000 STB/day (95% confidence interval) with a corresponding best estimate of 70,000 STB/day for the time period following cutting of the riser and drill pipe but prior to placement of the top hat (1–3 June)

These represent reconciled ranges based on independent estimates from multiple national labs using a statistical analysis by NIST.

The estimates for these time periods were also analyzed with respect to two end-member scenarios for flow in the wellbore, which resulted in a bimodal distribution of estimates.

The wide spectrum of approaches used to estimate flow exhibited good agreement on a benchmarking scenario (*e.g.*, with a standard deviation of ~6% on estimated rates).

The large range in the estimates of flow related primarily to uncertainty associated with the well failure mechanism and, hence, the flow scenario within the well. Specifically, estimates were highly dependent on whether flow occurred primarily inside the casing or in the annular space outside the casing.

In addition, several uncertain and/or variable parameters were important in the estimation of flow, including bottom-hole pressure (which relates in part to flow in the reservoir), resistance in the blowout preventer, casing roughness, and gas-oil ratio. The Nodal-Analysis Team flow estimates include considerations of these parameters.

2.0 Background

The Nodal-Analysis Team is part of the Flow Rate Technical Group (FRTG), which was asked to estimate the flow rates from the Deepwater Horizon MC-252 well. The Nodal-Analysis Team was tasked with providing an estimate of flow rate by nodal analysis of the flow from the reservoir to the release points; another team (the Reservoir-Modeling Team, led by Minerals Management Service or MMS²) was tasked with estimating flow within the reservoir.

¹ As with all estimates in this report, these estimates assume a constant reservoir pressure over time.

² MMS has become Bureau of Ocean Energy Management or BOEM.

Nodal-Analysis Summary

The Department of Energy was asked by the FRTG to lead the Nodal-Analysis Team, so DOE's Assistant Secretary for Fossil Energy engaged a team of five DOE national labs that have been collaboratively addressing other fossil-energy challenges. These labs are:

- LANL—Los Alamos National Laboratory
- LBNL—Lawrence Berkeley National Laboratory
- LLNL—Lawrence Livermore National Laboratory
- NETL—National Energy Technology Laboratory
- PNNL—Pacific Northwest National Laboratory

Experts at a sixth national lab (ORNL—Oak Ridge National Lab) were engaged to provide a peer-review of the work (as requested by the FRTG). As the DOE-FE lab, NETL was asked to lead this multi-lab effort. Statistics experts at the National Institute of Standards and Technology (NIST) provided an analysis of the pooled estimates for some time periods in order to arrive at a single estimate for each time period.

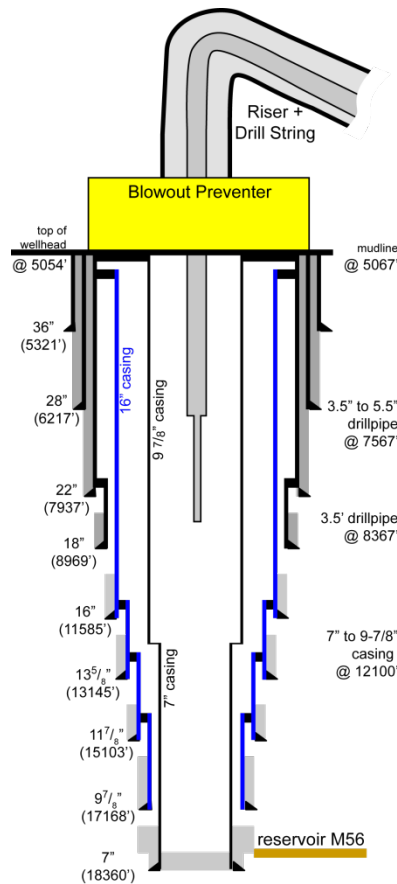


Figure 1: Schematic diagram of the system evaluated by the Nodal-Analysis Team (based on well schematic details from BP as available on <http://www.energy.gov/open/oilspilldata.htm>).

Using five different but comparable methodologies, the Nodal-Analysis Team focused on an estimate of fluid flow (including oil flow) from the reservoir to the release point(s), based on pressure drops from the reservoir to the ocean floor that result from restriction

Nodal-Analysis Summary

to flow through the reservoir-well-BOP³-riser system (Fig. 1). As noted, the MMS-led Reservoir-Modeling Team conducted detailed analysis of the reservoir flow; these results were used to inform the Nodal-Analysis Team with respect to some details of reservoir processes. Specifically, the link between reservoir and well relates to the coupling of flow rates out of the reservoir as a function of bottom-hole pressure, which is in turn a function of flow conditions in the well. To address this coupling, reservoir flow was incorporated into each of the nodal-analysis models to varying degrees and using different approaches. In addition, predictions from the Nodal-Analysis Team were made for a wide range of bottom-hole pressures to allow flexibility in comparisons with anticipated Reservoir-Modeling Team results.

3.0 General Approach

The five DOE national labs comprising the Nodal-Analysis Team used a diverse set of approaches to predict fluid flow (including two-phase flow, as relevant) through the various parts of the system. Each lab engaged a diverse team of its scientists and engineers, resulting in five separate teams estimating the flow.

Detailed discussions occurred across the Nodal-Analysis Team with respect to conceptual descriptions of the system, data needs, computational approaches, etc., providing an element of inter-lab peer review. Each individual lab team estimated flow rates independently. After the individual lab teams had conducted their analyses, flow estimates were discussed across the Nodal-Analysis Team to develop the conclusions as outlined in this summary report.

3.1 Data

Data used in the estimates⁴ included a set of proprietary reports provided by MMS:

- Reservoir data included pressure (P), temperature (T), depth range, permeability, and porosity. Data sources included a wellbore schematic prepared by BP (now publicly available; listing depths and T), a report prepared for BP by Weatherford Laboratories (listing permeability/porosity at various depths), a wire-line log (which included porosity and permeability as a function of depth), a report prepared for BP by Schlumberger (listing reservoir pressures and temperatures), and verbal communication from MMS (confirming reservoir pressure and temperature).
- Fluid data included chemical analysis and fluid properties of the produced hydrocarbon (including component hydrocarbon percentages, gas-to-oil ratio, density, viscosity, compressibility, Pressure-Volume-Temperature (PVT) relationships for reservoir fluids, API gravity, properties at reservoir conditions, bubble-point pressure). Data sources included reports prepared for BP by Schlumberger and Pencor. Each team developed its own method to describe fluid

³ BOP: Blowout Preventer

⁴ Details of the data are discussed in confidential reports from each of the individual lab teams; these proprietary data are *not* described in detail in this Summary Report.

Nodal-Analysis Summary

- properties throughout the system, consistent with the observed properties as reported.
- Well geometry data included the depths and sizes of casings and liners, cement zones, depths and sizes of drill pipe, T as a function of depth, and geometry of the BOP. The primary data source was a schematic prepared by BP (now publicly available).
 - BOP data included a report on pressure measurements made at various points in the BOP on 25 May 2010.⁵ This information was used to establish potential pressure drops associated with the BOP at one-point-in-time for a given set of conditions.

3.2 Computational Models

All five approaches accounted for the physics of two-phase fluid flow (as necessary).

Three of the five approaches (LANL, LLNL, and NETL) utilized models of the well system that accounted for reservoir coupling through the relationship between bottom-hole pressure and flow rate (Inflow Performance Relationship, or IPR). A preliminary IPR was calculated by NETL (Fig. 2) based on a black-oil model and a 17-layer reservoir model using site characteristics from a wire-line log. Two of the five approaches (LBNL and PNNL) utilized a coupled reservoir-well model.

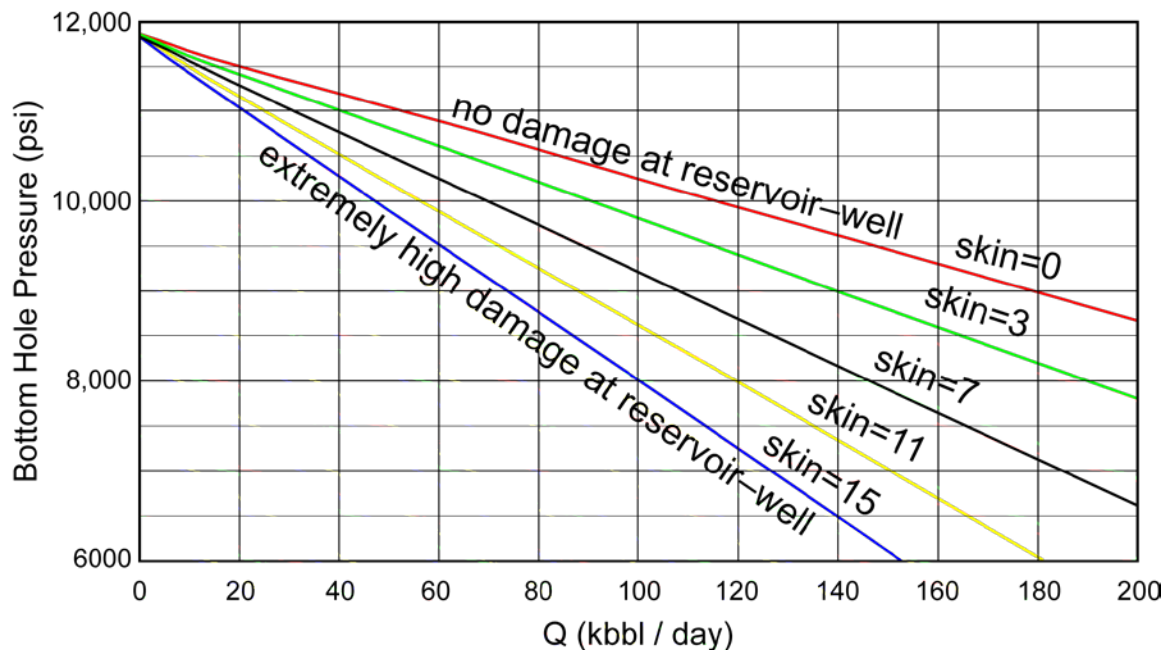


Figure 2: Inflow Performance Relationship at simulation day 15 calculated for the Deepwater Horizon site based on a black-oil simulator and a 17-layer reservoir model built in CMG. Skin factor is a parameter used to account for resistance between the reservoir and the well, usually associated with damage at the interface. A skin of 0 corresponds to no damage, whereas a skin of 15 corresponds to extremely high damage. A skin of 3 would be a commonly expected value.

⁵ As reported on <http://www.energy.gov/open/oilspilldata.htm>.

A summary of the different approaches follows:

- LANL—a parametric engineering model to predict volumetric two-phase flow rates of oil and gas through both known and postulated restrictions in the wellbore system and associated pressure losses; flow estimates were calculated as a function of bottom-hole-pressure; oil properties were described following Dindoruk & Christman (2004) along with data from Schlumberger for the Macondo MC 252 well; gas properties were described following Peng-Robinson (1972) and Jossi et al. (1962).⁶
- LBNL—a coupled wellbore-reservoir flow model based on the Drift-Flux Model and modified to handle oil-gas systems and to handle uncertainty quantification and sensitivity analysis
- LLNL—a two-phase flow model based on BP oil property data for flow within the well system, including the effects of heat transfer to the surrounding rock, and reported pressure drops across the BOP; flow estimates were calculated as a function of bottom-hole pressure
- NETL—a parametric facility model (including well, BOP, riser, and drill pipe) developed using Pipesim™ and tied to the reservoir through an IPR curve to describe the behavior of flow in the reservoir (*i.e.*, flow estimates were calculated as a function of bottom-hole pressure)
- PNNL—a coupled reservoir-well model to estimate the frictional pressure drop(s) within the wellbore system using the revised Beggs and Brill two-phase flow model, given an assumed stock oil production rate; oil properties were described following Standing's correlation for bubble point, Glaso for dead oil, Beggs-Robinson and Vasquez-Beggs for saturated oil; gas properties were described following Dranchuk and Abu-Kassem for compressibility and density and the Lee-Gonzalez-Eakins method for viscosity.

3.3 Time Periods with Different Flow Conditions

The well has experienced different flow conditions over several time periods that were considered by the various teams (Table 1). In addition, some simulations were done by each team for a hypothetical situation representing no BOP (*i.e.*, no ΔP across the BOP).

⁶ See Appendix for references: *Report on Estimation of Oil Flow Rate from British Petroleum (BP) Oil Company's Macondo Well* prepared by Los Alamos National Laboratory.

Table 1: Comparison of Simulations Conducted for Different Modeling Periods/Flow Conditions

<i>Time Period</i>	<i>Description</i>	<i>Dates</i>	<i>LANL</i>	<i>LBNL</i>	<i>LLNL</i>	<i>NETL</i>	<i>PNNL</i>
1	After explosion prior to rig collapse	20 Apr– 22 Apr	X				
2	Post rig collapse but prior to partial closure of BOP	22 Apr– 25 Apr	X				
3	Post partial closure of BOP but prior to capping of drill pipe	25 Apr– 05 May	X		X	X	
4	Post capping of drill pipe but prior to cutting of riser	05 May– 01 Jun	X			X	
5	Post cutting of riser but prior to placing top hat	01 Jun– 03 Jun	X	X	X	X	X
6	Post cutting of riser with top hat in place	03 Jun–				X	

3.4 Conceptual Flow Models

The Nodal-Analysis Team assumed that the well was not originally open to flow from the reservoir (based on reports that it had not been perforated). Hence, uncertainty exists as to the mechanism by which hydrocarbon fluids enter the well system. Based on expert opinion, we considered various plausible flow scenarios that could represent flow paths of fluids exiting the riser after entering the well-BOP-riser system either through: (a) the wellhead seal assembly at the top of the well, (b) the 7” casing at the bottom of the well, or (c) the 9-7/8” casing along the well. These scenarios result in two end-member flow conditions: (1) dominantly annular flow outside of the completion casing (Fig. 3a) or (2) dominantly pipe flow inside the completion casing (Fig. 3b). We also considered an intermediate scenario where flow initiates in the annular region and then enters the completion casing at a point along the well (Fig. 3c). Some of the teams simulated all three well-flow scenarios; some teams simulated one of the scenarios.

Flow conditions within the BOP were not modeled in detail. Instead, the effect of restrictions in the BOP was modeled either as a uniform pressure drop across the BOP or as a very small diameter pipe. Pressure measurements reported for the BOP on 25 May 2010 provided a baseline for the ΔP at one point in time. However, due to the potential for variation in the BOP pressure drop over time, teams assessed flow over a range in BOP pressure drop.

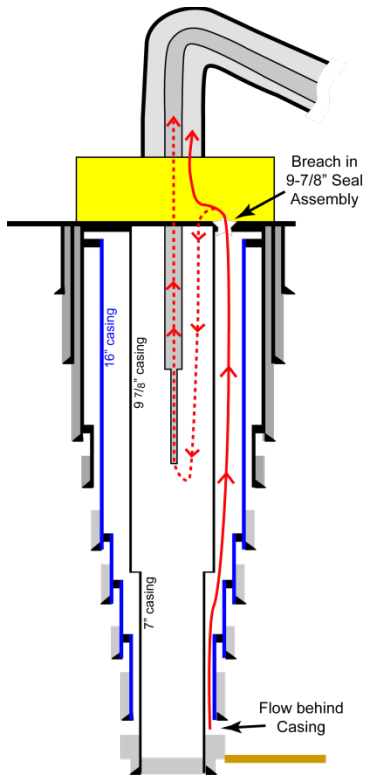


Figure 3a: Schematic diagram of well flow for Scenario 1. Flow initiates in the annular space between liner and casing, flowing through a breach at the top (in the seal assembly) into BOP and then riser; depending on flow restrictions in BOP, some flow may re-enter the casing to flow down to enter the drill pipe.

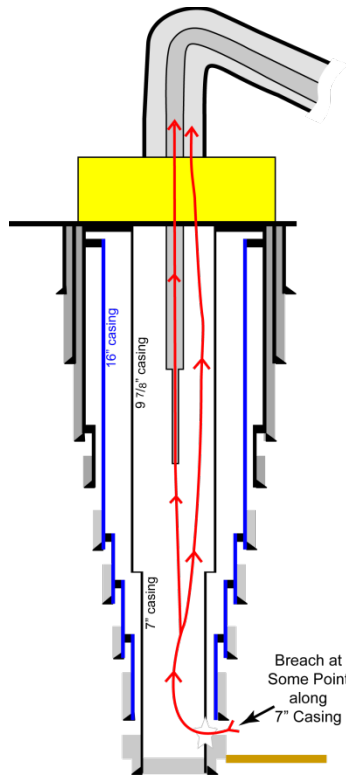


Figure 3b: Schematic diagram of well flow for Scenario 2. Flow initiates in a breach of the 7" casing, flowing up the casing. Some flow enters drill pipe, some continues up the casing to BOP.

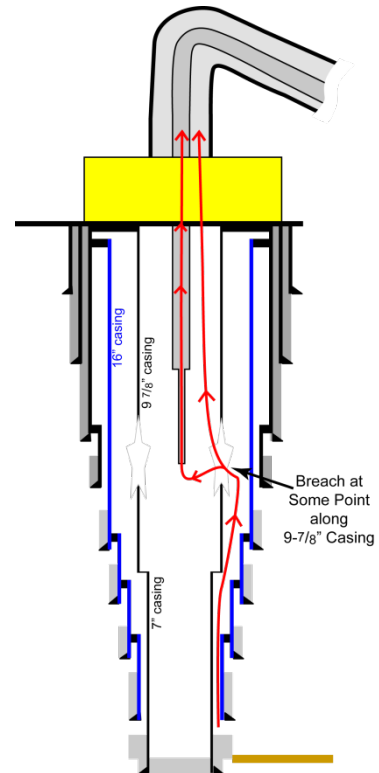


Figure 3c: Schematic diagram of well flow for Scenario 3. Flow initiates in the annular space between liner and casing, entering a breach in 9-7/8" casing and continuing to flow upward inside the casing. Some flow enters drill pipe, some continues up the casing to BOP.

4.0 Conclusions

4.1 Flow Dynamics in Well

All models predicted two-phase flow in the upper portion of the well, which is consistent with reported bubble point pressures for the reservoir hydrocarbon and with the reported pressure of 4400 psi measured at the bottom of the BOP on 25 May 2010.⁷ Determining and accounting for the vertical distribution of single phase and two-phase flow was important to estimating the flow rates.

⁷ See "Pressure Data Within BOP" at <http://www.energy.gov/open/oilspilldata.htm> (filename: "4.2_Item_1_BOP_Pressures_07_Jun_1200_Read_Only.xls")

Nodal-Analysis Summary

4.2 Choice of Conceptual Flow Model

Teams that compared scenarios found that flow scenario 2 (Fig. 3b) resulted in the highest flow rate by a factor of 1.5–2 over flow scenarios 1 or 3. Additionally, scenarios 1 & 3 produced roughly the same flow estimates.

4.3 Consensus Flow Rates

To develop a consensus flow rate, the Nodal-Analysis Team recognized the variety of potential flow scenarios and time periods, as well as the variety of estimation approaches used by the individual lab teams. This variability precluded the development of a consensus flow rate based simply on comparison of predicted ranges reported by each team. Instead, a set of Nodal-Analysis Team flow rates was developed based on considerations discussed below. In addition, the Nodal-Analysis Team engaged statistical experts at the National Institute of Standards and Technology (NIST) to assist in developing a set of flow rates consistent with the various estimation results from each lab team for time periods where multiple teams made estimates of flow.

The Nodal-Analysis Team concluded that two primary factors should be considered in assessment of flow rates: choice of time period (Table 1) and choice of flow model within the well (Figs. 3a–3c):

- The Nodal-Analysis Team concluded that flow rates for the different time periods would likely differ due to fundamental differences in the flow characteristics of the system. Consequently, flow rates should be considered specifically for each time period. Time period 5 (post cutting of the riser and prior to installation of the top hat) was the only time period for which all teams assessed rates. Consequently, this time period was initially used for comparing the various estimation approaches. In addition, it was concluded that estimates of flow rates for other time periods would be determined using estimates from subsets of the Nodal-Analysis Team (as available).
- With respect to choice of flow pathway, the Nodal-Analysis Team had little basis upon which to evaluate whether any one of the three flow scenarios considered were most likely. However, the clear difference in rates between scenario 2 and scenarios 1 & 3 was used as a consensus observation by the Nodal-Analysis Team to exploit in developing the definition for a consensus rate. Specifically, it was agreed that an estimate for the lower bound of flow rate should be based on the lower bound for scenarios 1 and/or 3, whereas an estimate for the upper bound of flow rate should be based on of the upper bound for scenario 2.

In addition, the Nodal-Analysis Team chose to determine these lower and upper bounds using an expert-elicitation process, whereby each team would be treated as a separate expert group and report its estimated rates using the following guidance:

- A lower bound should represent the 5th percentile level, whereas an upper bound should represent the 95th percentile level. In cases where no Monte Carlo analysis was done, these values were based on expert judgment within the individual lab team on rates corresponding to conditions consistent with a 90% confidence

Nodal-Analysis Summary

interval. Individual lab teams then reported low and high values independently, and these were then analyzed in composite to arrive at a consensus range of rates for the 90% confidence interval.

Table 2 shows the results of this composite analysis.

Table 2: Summary of (composite) flow estimates** for various time periods (Table 1).

		<i>Low Estimate</i>	<i>High Estimate</i>	<i>Assumptions</i>
<i>Time Period 1</i>	LANL	55,000	112,000	Low estimate is lowest value of 5 th percentiles for scenarios 1 & 3; high estimate is 95 th percentile value for scenario 2
<i>Time Period 2</i>	LANL	49,000	100,000	Low estimate is lowest value of 5 th percentiles for scenarios 1 & 3; high estimate is 95 th percentile value for scenario 2
<i>Time Period 3</i>	LANL	42,000	90,000	Low estimate is lowest value of 5 th percentiles for scenarios 1 & 3; high estimate is 95 th percentile value for scenario 2
	LLNL	45,000	83,000	assuming low/high values of skin (0/15) and roughness (dimensionless roughness = 0.0002/0.002)
	NETL	45,000	87,000	5 th and 95 th percentile using populations derived from extensive parametric study
<i>Time Period 4</i>	LANL	39,000	81,000	Low estimate is lowest value of 5 th percentiles for scenarios 1 & 3; high estimate is 95 th percentile value for scenario 2
	NETL	(N/A)	80,000	95 th percentile using population derived from extensive parametric study
<i>Time Period 5</i>	LANL	46,000	96,000	Low estimate is lowest value of 5 th percentiles for scenarios 1 & 3; high estimate is 95 th percentile value for scenario 2
	LBNL	(N/A)	120,000	based on 500 M-C simulations of the system with well screened across entire thickness of the reservoir and no BOP pressure losses
	LLNL	46,000	85,000	assuming low/high values for skin (0/15) and roughness (dimensionless roughness = 0.0002/0.002)
	NETL	45,000	100,000	5 th and 95 th percentile using populations derived from extensive parametric study
	PNNL	30,000	110,000	based on expert opinion: using lower values than median calculation for scenario 3; estimating higher possible flows from plausible ranges of input parameters for scenario 2

** Results are presented to two significant figures.

Table 2a: Summary of flow estimates** for time periods 3 and 5.

		<i>Scenarios 1/3</i>		<i>Scenario 2</i>		<i>Assumptions</i>
		<i>Low Estimate</i>	<i>High Estimate</i>	<i>Low Estimate</i>	<i>High Estimate</i>	
<i>Time Period 3</i>	LANL	42,000	54,000	67,000	90,000	Low/high estimates are lowest/highest value of 5th/95th percentiles for scenarios 1 & 3 and for scenario 2
	LLNL	45,000	55,000	64,000	83,000	Low/high estimates assume high/low values for skin (15/0) and roughness (0.002/0.0002 inches)
	NETL	46,000	63,000	61,000	86,000	Low/high estimates are lowest/highest value of 5th/95th percentiles for scenarios 1 & 3 and for scenario 2; slight variations from numbers in Table 2 reflect updated calculations based on new information from MMS
<i>Time Period 5</i>	LANL	46,000	56,000	73,000	96,000	Low/high estimates are lowest/highest value of 5th/95th percentiles for scenarios 1 & 3 and for scenario 2
	LBNL	(N/A)	(N/A)	90,000	118,000	Based on 37-m open borehole
	LLNL	46,000	56,000	66,000	85,000	Low/high estimates assume high/low values for skin (15/0) and roughness (0.002/0.0002 inches)
	NETL	45,000	64,000	62,000	96,000	Assuming min/max values for cases examined corresponded to P ₀₁ /P ₉₉ values of a Gaussian distribution; standard deviation was based on a standard normal table, with mean taken as average of P ₀₁ /P ₉₉ (symmetric) and where P ₀₁ /P ₉₉ correspond to a Z-value of 2.33 (Freund, 1992, Mathematical Statistics)
	PNNL	30,000	55,000	44,000	110,000	Low for scenarios 1/3 is reduction in lowest case by 20% to account for uncertainty; low for scenario 2 is low permeability/high BOP pressure loss case with 2000 psi breach pressure loss (which was judged to be sufficiently conservative that no further reduction was made for uncertainty in other parameters); high values represent a 30% increase in high permeability/high BOP pressure loss case to account for potential lower BOP losses, tendency of the model to underpredict flow rate, and uncertainty in GOR

** Results are presented to two significant figures.

Nodal-Analysis Summary

For those time periods where multiple lab estimates were made (time periods 3 and 5), NIST developed a single, reconciled estimate using a statistical procedure for pooling results from multiple assessments. Using this procedure, NIST calculated the following:

- 40,000–91,000 STB/day has a 95% probability of including the true value of the flow rate for time period 3, with a corresponding best estimate of 65,000 STB/day
- 35,000–106,000 STB/day has a 95% probability of including the true value of the flow rate for time period 5, with a corresponding best estimate of 70,000 STB/day

An additional analysis was done to break out the estimates for time periods 3 and 5 into separate estimates for scenarios 1/3 and scenario 2 (Table 2a), thus providing more granularity to the estimates. This breakout was based on the recognition that these scenarios represent end-member cases reflecting flow that is dominantly in the annular space between the completion casing and the outer casing (blue in Fig. 3) or flow that is dominantly inside the completion casing. These end-member scenarios resulted in two distinct distributions in flow estimates. Using the same procedure described above, NIST calculated the following (Figs. 4ab):

- 42,000–62,000 STB/day has a 95% probability of including the true value of the flow rate for scenarios 1/3, time period 3, with a corresponding best estimate of 51,000 STB/day
- 61,000–90,000 STB/day has a 95% probability of including the true value of the flow rate for scenario 2, time period 3, with a corresponding best estimate of 75,000 STB/day
- 33,000–62,000 STB/day has a 95% probability of including the true value of the flow rate for scenarios 1/3, time period 5, with a corresponding best estimate of 50,000 STB/day
- 53,000–120,000 STB/day has a 95% probability of including the true value of the flow rate for scenario 2, time period 5, with a corresponding best estimate of 84,000 STB/day

Nodal-Analysis Summary

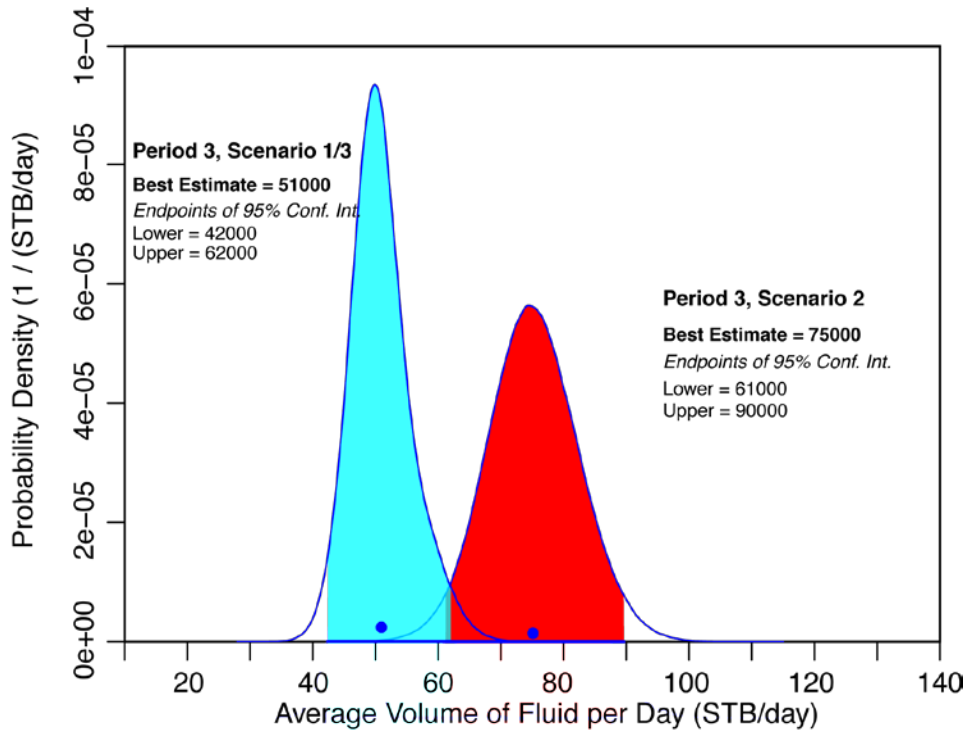


Figure 4a: Summary of NIST results for pooled estimates of flow for end-member cases (scenarios 1/3 and scenario 2) for time period 3.

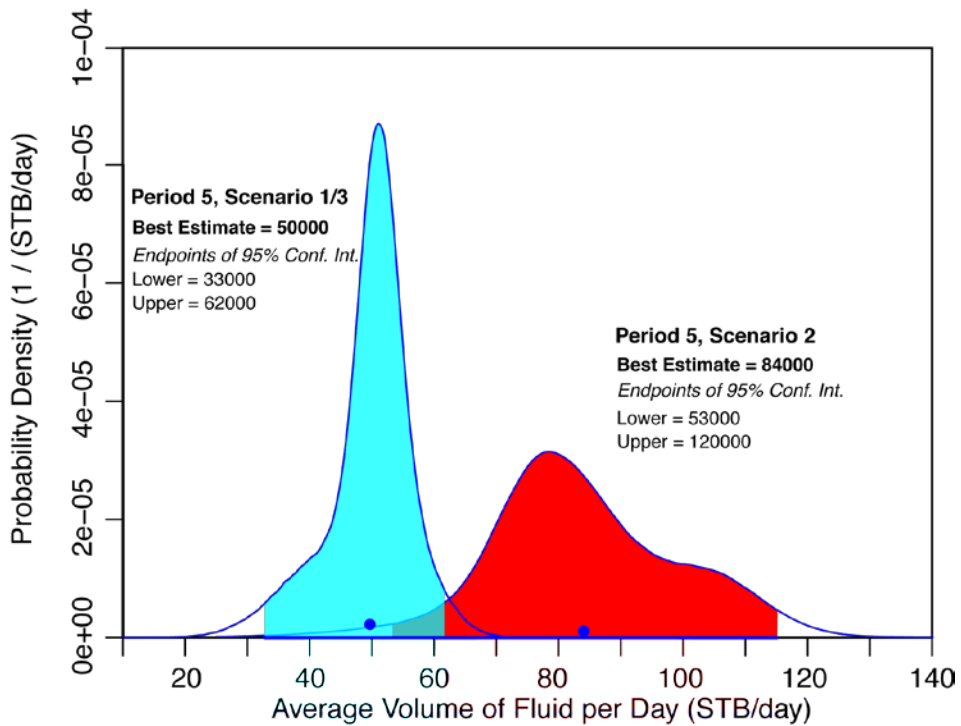


Figure 4b: Summary of NIST results for pooled estimates of flow for end-member cases (scenarios 1/3 and scenario 2) for time period 5.

Nodal-Analysis Summary

4.4 Sensitivity Analysis for Key Parameters

4.4.1 Benchmark Case

One scenario was chosen as a standard for comparing the independent modeling approaches. It was not selected to indicate any conclusion or consensus by the Nodal-Analysis Team that these particular conditions and resulting flow rates were more or less likely than any other. Rather, a set of conditions common to existing calculations by one of the teams (PNNL) were chosen for calculations by three of the other teams in order to provide a set of calculations for comparison. For the benchmarking runs, key variables were set to values consistent with the site; these included: API gravity, specific gravity of gas, ocean pressure and temperature (at the release point), reservoir temperature, bubble point, gas-oil ratio, bottom-hole pressure, pipe roughness, and pressure drop (ΔP) across the blowout preventer.

Further, a sensitivity analysis for critical uncertain and/or variable parameters (gas-oil ratio or GOR, BOP pressure drop, BHP,⁸ and roughness) was conducted by each of the teams using a distribution of values around those used in the initial benchmarking case. Distributions used in the sensitivity analysis were determined by Nodal-Analysis Team based on expert judgment and available data on MC252. Although some labs conducted sensitivity analyses as part of their initial detailed investigations, these analyses investigated a variety of flow conditions and/or ranges in parameters (in some cases, large ranges whereas in other cases smaller ranges). This variability precluded an integrated sensitivity assessment by the Nodal-Analysis Team based, so this additional sensitivity analysis was undertaken.

Four of the five labs⁹ performed simulations at or near the benchmark case conditions. The results from the benchmarking study are shown in Table 3. Model predictions agreed very well for this case, with a standard deviation of ~6%. The lab reporting the highest estimate used slightly different input values, one of which (GOR) would have biased their results upward (as based on the sensitivity analysis described below).

⁸ BHP=Bottom hole pressure (in the well)

⁹ LBNL was unable to participate in this set of benchmarking simulations or in the associated sensitivity analysis, although LBNL (as well as each of the lab teams) performed an independent uncertainty and sensitivity analysis.

Table 3: Benchmarking results **

<i>Oil Flow Rates for Benchmark Case (STB/day)</i>	
LANL	73,000
LLNL *	75,000
NETL	70,000
PNNL	65,000
Mean	71,000
σ	4,300
σ/Mean	6%

* LLNL results correspond to values for some of the fluid properties that are comparable to those used by the other teams but differ slightly

** Results are presented to two significant figures

Table 4: Results ** for sensitivity analysis around benchmark case. Values are in STB/day. “Low” and “High” correspond to the values determined using the low and high value of the parameter investigated (respectively), as defined in Table 3.

<i>Parameter</i>	<i>LANL</i>		<i>LLNL*</i>		<i>NETL</i>		<i>PNNL</i>	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
GOR	80,000	72,000	n/a	n/a	78,000	69,000	73,000	65,000
BOP	84,000	69,000	86,000	71,000	82,000	66,000	76,000	61,000
BHP	50,000	88,000	61,000	86,000	49,000	85,000	40,000	81,000
Roughness	77,000	72,000	79,000	75,000	74,000	69,000	69,000	64,000

* GOR was not varied. All other parameters were as listed in Table 4 footnote.

** Results are presented to two significant figures.

Table 5: Percent change for flow rate going from low end of parameter range to high end of range.

<i>Parameter (range)</i>	<i>LANL</i>	<i>LLNL</i>	<i>NETL</i>	<i>PNNL</i>
GOR (2300–3150 scf/STBO)	10%	n/a	11%	11%
BOP (1000–2500 ΔP , psi)	17%	17%	19%	20%
BHP (8500–11500, psi)	–77%	–40%	–73%	–103%
Roughness (0.001–0.002 inches)	6%	5%	6%	7%

Nodal-Analysis Summary

Table 4 shows the results of a sensitivity analysis performed around the benchmark case for the four critical parameters. “Low” and “High” values denote flow rates that correspond to the minimum and maximum values of the ranges for the varied parameters (not the minimum and maximum flow rates themselves). Table 5 shows the percent change in the flow rates for the high value of the parameter relative to the low value. Conclusions drawn from the values in Tables 4 and 5 are only strictly valid for the range of parameters.

4.4.2 Impact of Gas-Oil Ratio (GOR)

All teams found that changing the GOR had a noticeable impact on the flow rate estimate. Higher GOR produced lower flow estimates. For the range of GOR studied in the sensitivity analysis, the flow rates for each model only varied by 10–11% (Table 5), suggesting only a moderate impact on the flow rate estimates for that range. In contrast, LBNL (in its separate sensitivity analysis) found that GOR was the second most important variable in determining flow rate, albeit LBNL’s analysis spanned a much larger range (1000–3017 scf/STBO).

4.4.3 Impact of Blowout Preventer (BOP)

All teams found the resistance (or the resulting ΔP) across the BOP impacted flow rate. Higher resistance in (or ΔP across) the BOP produced lower flow estimates. For the range of pressure drops studied in Table 3, the flow rates for each model varied by 17–20% from lowest to highest, suggesting that the pressure drop across the BOP has a fairly substantial effect on the flow rate estimates for the range of values used. The relatively high sensitivity to BOP partly reflects the broad range over which BOP pressure drop was varied in the sensitivity study (given that it was one of the most uncertain parameters). One model (LBNL) predicted a relatively low sensitivity to BOP over this range (albeit not at the exact conditions of the benchmarking case). LBNL concluded that the reason for this lack of sensitivity to BOP pressure under two-phase conditions is the phase interference caused by gas. Specifically, as the pressure at the bottom of the BOP decreases (less constriction), the ΔP from reservoir to seafloor increases, which should increase oil flow rate, but at the same time more gas exsolves, which inhibits oil flow.

4.4.4 Impact of Bottom Hole Conditions

All teams determined that the bottom-hole conditions had a significant impact on the estimates of oil flow rate. In the flow estimation, each team varied these conditions in different ways, either through reservoir pressure, permeability, skin factor, length of open interval (effective screen), or directly through bottom-hole pressure (BHP). In the sensitivity study, bottom-hole pressure was used. Higher BHP produced lower flow estimates. Of the four variables studied in the sensitivity analysis, BHP clearly has the greatest effect on the results. This finding underscores the importance of accurately capturing reservoir conditions in the nodal analysis results.

The importance of bottom-hole flow conditions was also found by LBNL in its separate sensitivity analysis using a different set of parameter ranges and a coupled wellbore-

Nodal-Analysis Summary

reservoir model. In LBNL's assessment reservoir permeability (as a controlling factor in bottom-hole flow conditions) was the most important parameter in estimating flow rate for scenario 2.

4.4.5 Impact of Roughness Parameter for Pipes

All teams found that the value for roughness used to account for frictional pressure loss along the well had an impact on estimates of flow rate. Higher roughness produced lower flow estimates. In the calculations used to estimate flow as reported in Table 2, slight variations were used in the simulations by each team:

- LANL—simulations used a roughness of 0.00138 inches; to assess impact on flow rate, simulations using a roughness of 0 showed an increase in flow rate of ~20% for scenarios 1 & 3 and ~25% for scenario 2
- LBNL—simulations used a roughness of $4.5\text{e-}5$ m (0.00177 inches)
- LLNL—simulations used a dimensionless roughness of $2\text{e-}4$ in the well, drill pipe, and riser; simulations using a roughness of 0 indicated an increase in flow of ~20%; for the well, $2\text{e-}4$ corresponds to roughnesses of 0.001219 inches for an ID of 6.094" (7" casing) and 0.001725 inches for an ID of 8.625" (9-7/8" casing)
- NETL—simulations used a roughness of 0.001 inches
- PNNL—simulations used a roughness of 0.0018 inches in the drill-pipe and casing; for the annular region in the lowest section of scenario 3 (from the entry point to the bottom of the 9-7/8" liner at ~17,168'), roughness was a weighted average of steel (0.0018 inches) and concrete (0.12 inches) to account for exposed rock along the outer wall of the well.

In the sensitivity analysis, the range of values assessed spanned the range used by the teams in the flow estimation; over this range, the effect of roughness was 5–7% on the flow estimates.

4.4.6 Impact of Riser + Drill Pipe

With respect to components of the system downstream of the BOP (*e.g.*, bent riser and drill pipe assembly), the most significant assumptions related to the nature of the kink in either the riser or the drill pipe. The Nodal-Analysis Team addressed this by reducing the effective cross-sectional area in the two flow paths at the point of the kink.

Although this factor was not specifically considered in the sensitivity analysis around the benchmarking case, a qualitative assessment based on the team results in the flow estimation suggested that the pressure drop was generally small across the kink in the riser, and across the riser in general. However, the pressure drop due to the kink in the drill pipe was more significant if a substantial restriction were assumed (*i.e.*, a restriction $\geq 90\%$). Nevertheless, the overall pressure drop summed over the riser and drill pipe assembly was relatively minor, as can be assessed by comparing flow estimates for time period 5 (post cutting of the riser and drill pipe) with time periods 3 and 4 (Table 2).

4.5 Assessment of Results from Reservoir Modeling Team

Results from the Reservoir Modeling Team included a range of IPR curves representing different conditions (Fig. 5).

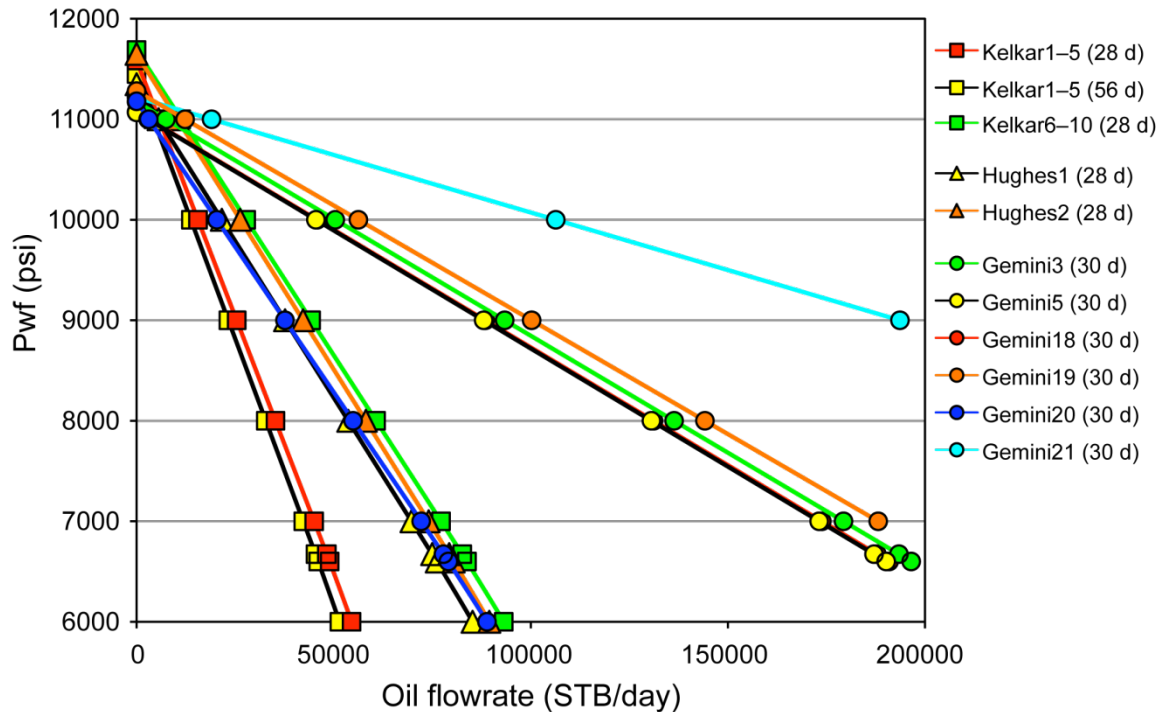


Figure 5: Inflow Performance Relationships (IPRs) from the Reservoir Team models. Gemini=Gemini Solutions; Kelkar=Kelkar and Associates; Hughes=R.G. Hughes and Associates. Pwf=Pressure while flowing.

The IPRs from the Reservoir Modeling Team fell into four general groups:

1. A group of curves that include Gemini-3, -5, -18, and -19. These used a base-case permeability for the reservoir.
2. An upper curve corresponding to the Gemini-21 IPR, which used a permeability twice that used in the base case.
3. A group of curves that include Gemini-20 as well as Kelkar IPRs for cases 6–10 and the two Hughes IPRs. For the Gemini and Kelkar IPRs, this group corresponded to a permeability roughly 40% lower than the Gemini base cases. For the Hughes IPR, this corresponded to an oil-wet system but using absolute permeability values comparable to the Gemini base case.
4. The lowest group of IPR curves that include the Kelkar IPRs for cases 1–5 using Kelkar’s base case permeability values, which were roughly 65% lower than those in group 3 or ~25% lower than the Gemini base case values (group 1).

In general, several observations can be made in comparing the Reservoir Modeling Team IPRs with the NETL developed IPRs used by the Nodal Analysis Team (Fig. 2):

Nodal-Analysis Summary

- The Gemini 21 curve was comparable to the NETL IPR for skin 0. This Gemini curve corresponded to an upper end for reservoir permeability (slightly higher than that used by the NETL model¹⁰) and an infinitely behaving reservoir (*i.e.*, the maximum anticipated case for reservoir flow). Based on this, the Nodal Analysis Team concluded that the results from the Reservoir Analysis Team do not significantly impact the nodal estimates of the high end of the flow rate ranges.
- The Reservoir Modeling Team results demonstrate that reservoir permeability has a major impact on estimates of flow rate, confirming the LBNL sensitivity analysis using a coupled reservoir-well model that found permeability to be one of the two most important controls on flow rate.
- The primary factors driving the groups of IPR curves from the Reservoir Modeling Team related either to (a) assumptions of lower absolute permeability in the reservoir or (b) assumptions consistent with an oil-wet system (as opposed to a water-wet system). Assumptions by the Nodal Analysis Team were based on measured properties reported for one core from the reservoir (*i.e.*, the assumptions used were consistent with information available to the team). However, incorporation of the full range of properties explored by the Reservoir Modeling Team would decrease the lower estimates of flow based on nodal analysis.
- Several of the other Gemini curves (e.g., 3, 5, 18, 19) assessed reservoir boundary effects. These IPRs showed only a slight depression for smallest reservoir size considered by Gemini (based on detailed reservoir information). These Reservoir Modeling Team results suggest that the Nodal-Modeling-Team assumption of an infinitely acting reservoir was reasonable and relaxing that assumption would not have a big impact on estimates of rate.

¹⁰ Specifically, the product of absolute permeability and net-pay-zone thickness for the NETL IPR was only a factor of ~1.5 larger than this product for the Gemini-21 IPR. The NETL IPR was based on air permeability measurements as reported by a core analysis provided by MMS and assuming they represented midpoints of flow units along the core; the Gemini IPRs used three different permeabilities taken from within the range of reported air permeability measurements and applied these to the net pay zone thickness as determined by MMS. The relative permeability curves for oil were comparable between the NETL and Gemini cases.

5.0 Flow-Estimate-Team Bios

5.1 LANL—Los Alamos National Laboratory

Dr. Rajesh Pawar is a Senior Project Leader in the Earth & Environmental Sciences Division at Los Alamos National Laboratory. His research interests are in the area of sub-surface fluid flow simulations as applied to oil & gas reservoir simulations, CO₂ sequestration, and enhanced oil recovery.

Dr. John Bernardin is a Scientist in the Mechanical and Thermal Engineering Group in the Applied Engineering and Technology Division at Los Alamos National Laboratory. He has a Ph.D. in Mechanical Engineering from Purdue University. His Ph.D. thesis is in the area of boiling heat transfer and two-phase flow. During his 14 years at LANL he has specialized in heat transfer and fluid mechanics including both experimental techniques and numerical modeling. He has over 60 peer-reviewed publications on various topics within the field of Mechanical Engineering. He is currently an Adjunct Professor at the University of New Mexico – Los Alamos and also President of Engineering & Technology Instruction, LLC.

Mr. Richard Kapernick is a Scientist in the Nuclear Design and Risk Analysis Group at Los Alamos National Laboratory. He has worked on the thermal-hydraulic design of nuclear reactors since 1968 at General Atomics and more recently at LANL. For 20 years, he was the manager of a reactor thermal-hydraulic design group, a reactor internals group and for core startup at the Fort St. Vrain reactor. At LANL, he has worked primarily on designs for small fast reactors for space and terrestrial applications.

Dr. Bruce Letellier is a Scientist in the Nuclear Design and Risk Analysis Group at Los Alamos National Laboratory. He has a Ph.D. in Nuclear Engineering from Kansas State University. He has performed accident-phenomenology and health-consequence modeling for facility and weapon safety studies, and most recently PAR of geologic CO₂ sequestration. His past work has included interior- and atmospheric-transport modeling of aerosols and gases.

Dr. Robert Reid joined the technical staff at Los Alamos National Laboratory in 1986. Over his career he has work in areas such as convective two phase boiling enhancement, high temperature high pipes, thermoacoustic refrigeration, and fission reactor thermal hydraulic design for deep space missions. He received a Ph.D. in Mechanical Engineering from Georgia Tech and is a licensed professional engineer.

5.2 LBNL—Lawrence Berkeley National Laboratory

Dr. Curtis M. Oldenburg is a Staff Scientist and Program Lead for LBNL's Geologic Carbon Sequestration Program. Dr. Oldenburg received his PhD in geology from U.C. Santa Barbara in 1989, and has been working at LBNL since 1990. His area of expertise is numerical model development and applications for coupled subsurface flow and transport processes. He has worked in geothermal reservoir modeling, vadose zone hydrology, contaminant hydrology, and for the last ten years in geologic carbon sequestration. Dr. Oldenburg contributes to the development of the TOUGH codes.

Dr. Barry Freifeld is a Mechanical Engineer at the Lawrence Berkeley National Laboratory, where he is the principal investigator for numerous projects relating to CO₂ sequestration and arctic hydrology. He is an expert in the development of well-based monitoring instrumentation

Nodal-Analysis Summary

and techniques. His recent innovations include the U-tube geochemical sampling methodology, as well as thermal perturbation fiber-optic monitoring techniques for understanding subsurface processes. He has also received a U.S. patent for a portable whole-core x-ray computed tomography imaging system used at continental drill sites and on drilling vessels.

Dr. Karsten Pruess is a Senior Scientist at LBNL. He has conducted research in multiphase, non-isothermal, and chemically reactive flows in porous media, including mathematical modeling, analysis of field data, and laboratory experiments. His interests include geothermal energy recovery, nuclear waste isolation, oil and gas recovery and storage, environmental remediation, and geologic storage of carbon. He is the chief developer of the TOUGH family of general purpose simulation codes.

Dr. Lehua Pan has been working at LBNL since 1997 and is an expert in computer modeling of Earth systems and processes. Dr. Pan's research interests are in the area of new approaches to modeling fluid flow and transport in saturated and unsaturated soils, and porous and fractured media. Dr. Pan develops software to incorporate new approaches in subsurface modeling using cutting-edge IT techniques.

Dr. Stefan Finsterle is a Staff Scientist with research interests in inverse modeling of nonisothermal multiphase flow systems; fracture and unsaturated zone hydrology; hydrogeophysics; test design and data analysis; optimization; error and uncertainty analysis; and geostatistics. He is currently the Platform and Integrated Toolsets Deputy for Advanced Simulation Capability for Environmental Management (ASCEM) and is the main developer of the iTOUGH2 nonisothermal multiphase inverse modeling code.

Dr. George J. Moridis is a Staff Scientist at LBNL and is the Deputy Program Lead for Energy Resources and is in charge of the LBNL research programs on (a) hydrates and (b) tight gas, and (c) leads the development of the new generation of LBNL codes for the simulation of flow and transport in the subsurface. He is the author and co-author of over 45 papers in peer-reviewed journals, of over 145 LBNL reports and book articles, and of three patents. He is a SPE Distinguished Lecturer for the 2009-2010 period.

Dr. Matthew T. Reagan is a Geological Research Scientist with research focus on the thermodynamics, transport, and chemistry of aqueous systems in the subsurface, including research on the thermodynamics of gas hydrates, gas production from methane hydrate systems, the coupling of methane hydrates and global climate, carbon sequestration via subsurface CO₂ injection, data reduction and uncertainty quantification using statistical methods, and "tight gas" simulation and engineering. Built and maintain online tools for physical property estimation and numerical simulation.

5.3 LLNL—Lawrence Livermore National Laboratory

Dr. Todd Weisgraber is a staff engineer in the Center for Micro and Nano Technology at Lawrence Livermore National Laboratory. His research interests in computational physics span a variety of application disciplines, including underground coal gasification, rheology, polymer physics, and microfluidic systems.

Dr. Thomas Buscheck is the Group Leader of Geochemical, Hydrological, and Environmental Sciences in the Atmospheric, Earth, and Energy Division at Lawrence Livermore National Laboratory (LLNL). His research involves scientific/engineering model analyses of nonisothermal reactive flow and transport phenomena in fractured porous media, applied across a

Nodal-Analysis Summary

range of energy and environmental challenges, including underground coal gasification, geologic CO₂ storage, enhanced geothermal energy systems, and radioactive waste management.

Dr. Christopher Spadaccini is a member of the technical staff in the Engineering Directorate and the Center for Micro and Nano Technology at Lawrence Livermore National Laboratory. His primary research interests are thermal and fluid aspects of microsystems and porous media, microsensors for detection applications, and advanced transport phenomena.

Dr. Roger Aines leads LLNL's Carbon Fuel Cycle Program, which takes an integrated view of the energy, climate, and environmental aspects of carbon-based fuel production and use. It supports DOE projects in sequestration technology development for capture, and underground coal gasification.

5.4 NETL—National Energy Technology Laboratory

Brian J. Anderson has served as the Energy Resources Thrust Area Leader of the NETL Institute for Advanced Energy Solutions. He is the Verl Purdy Faculty Fellow and an Assistant Professor in the Department of Chemical Engineering at West Virginia University. He holds Masters and PhD degrees in Chemical Engineering from the Massachusetts Institute of Technology and a BS from West Virginia University. Dr. Anderson's research experience includes sustainable energy and development, economic modeling of energy systems, and geothermal energy development as well as molecular and reservoir modeling of energy-relevant systems such as natural-gas hydrates.

Dr. Grant S. Bromhal is the Research Group Leader of the Sequestration, Hydrocarbons, and Related Projects group in NETL's Geosciences Division. As such, he leads a team of researchers focused on modeling, experiments, and field research related to carbon sequestration and hydrocarbon recovery. Dr. Bromhal received his PhD in civil and environmental engineering from Carnegie-Mellon University and his BS/BA in civil engineering and math from West Virginia University. He is the recipient of the 2007 Hugh Guthrie Award for Innovation at NETL.

Dr. George Guthrie is the focus area leader for geological and environmental systems at the National Energy Technology Laboratory (NETL). Dr. Guthrie received his PhD in mineralogy from Johns Hopkins and his AB in geology from Harvard before working at Los Alamos National Laboratory for 19 years. Since joining NETL, he leads research activities across a range of fossil-energy related challenges, including CO₂ storage and unconventional fossil fuels (including environmental aspects related to oil/gas production).

Dr. W. Neal Sams joined NETL in 1987 and designs reservoir simulators and has extensive experience utilizing them in a wide range of applications, including carbon sequestration/enhanced coal bed methane production. He is the author of MASTER, a miscible flood simulator, and NFFLOW, a discrete fracture gas reservoir simulator. Sams holds B.S and Ph.D. degrees in physics from the University of Houston.

Dr. Doug Wyatt is the Focus Area Manager for Geological and Environmental Sciences for NETL and has ~30 years of experience in fossil energy exploration and production, the management of multidisciplinary teams responsible for energy research and policy support, and the geoscience and environmental evaluation of high hazard facilities. Wyatt is currently on the Executive Committee of the Division of Environmental Geology for the American Association of Petroleum Geologists. He is a Certified Petroleum Geophysicist. Wyatt holds an appointment as Research Professor and Lecturer in the Department of Biology and Geology at the University of South Carolina - Aiken and is an Adjunct Assistant Professor of Environmental Engineering and

Nodal-Analysis Summary

Earth Sciences at Clemson University. Dr. Wyatt has over 150 papers, presentations, and federal research reports.

Roy Long is NETL's Technology Manager for its Ultra-Deepwater and Unconventional Resources Program. He is a published Petroleum Engineer and well known within industry and the geoscientific community from his long association with technology development related to drilling and completion technologies. He is a 1970 graduate of the US Air Force Academy and received his MSc in Petroleum Engineering from the Colorado School of Mines. He is a member of many professional societies in the geosciences and has been a member of the Society of Petroleum Engineers for over 30 years.

5.5 PNNL—Pacific Northwest National Laboratory

Dr. Gauglitz joined PNNL in 1992 and is currently a project manager in the Fluid and Computational Engineering group in the Energy and Environment Directorate. He has led a variety of research and technology development projects, represented the laboratory to major clients, and has served as a technical group manager in the Environmental Technology Directorate for the Electrical and Chemical Processing and Thermal Processing groups and served as a technical group manager in National Security Directorate for the Radiation Detection and Nuclear Sciences group. A primary theme of his research interests has been the behavior of bubbles in non-Newtonian slurries, pastes, and porous media. Prior to joining PNNL, Dr. Gauglitz spent more than ten years investigating bubble behavior in porous media for enhanced oil recovery and in other oil field applications and worked for Chevron Oil Field Research Company. Dr. Gauglitz received a Ph.D. in 1986 from the University of California at Berkeley and a B.S. in 1981 from the University of Washington, both in Chemical Engineering.

Ms. Mahoney joined PNNL in 1989 and is a research engineer in the Fluid and Computational Engineering group in the Energy and Environment Directorate. She has played a central role in studies of waste retrieval through dissolution, flammable gas retention by in-tank waste, interpretation of data from waste pre-treatment processes in the test vitrification plant, definition of simulant compositions for a variety of tank waste studies, and computational modeling of chemical and flow systems.

Ms. Bamberger is a senior research engineer II in the Fluid and Computational Engineering group. Her research in multi-phase flow has focused on development and application of in-situ real-time instrumentation to characterize physical and rheological properties of particulate-laden fluids and multi-phase suspensions in both vessels and pipelines and developing fluids based technologies for remediating waste tanks. Ms Bamberger has an MS in Mechanical Engineering from The Pennsylvania State University and is a licensed Professional Engineer in the State of Washington.

Jeremy Blanchard joined PNNL in 2009 as a member of the Fluid and Computational Engineering group in the Energy and Environment Directorate. He has been involved in a number of diverse research projects including aerosol transport, multiphase pipe flow, flow in porous media, heat cycle analysis and building energy efficiency. His research interests are in experimental fluid mechanics and heat transfer applied to energy related projects. Specifically, he is focused on research relating to alternative energy and increasing building energy efficiency. Mr. Blanchard received a M.S. and B.S. in Mechanical Engineering from the University of New Hampshire in 2008 and 2006, respectively.

Nodal-Analysis Summary

Dr. Bontha is a Senior Research Engineer and a team-lead within the Radiochemical Science and Engineering group at PNNL. He has over 15 years experience in fluid dynamics, multi-phase slurry transport and mixing, and separations. Dr. Bontha has a Ph.D. in Chemical Engineering from Tulane University, New Orleans.

Mr. Enderlin has a Bachelor and Master's in Mechanical Engineering. Mr. Enderlin has a broad variety of project work experience including, experimental multi-phase fluid mechanics design and testing of systems, equipment for the mobilization mixing, transport, sampling of slurries as well as complex fluids and numerical simulation of thermal hydraulic systems. He has had International collaborations for spent fuel analyses equipment design and testing, performed analyses in the areas of: heat transfer and fluid mechanics, mechanical and system design, experimental design, data analysis, course development, and equipment evaluations. Mr. Enderlin has also developed test strategies, designed test setups, and directed test programs with both Newtonian and non-Newtonian fluids.

Dr. Fort is a staff engineer in the Fluid and Computational Engineering group at Pacific Northwest National Laboratory. His research activities are primarily in the area of computational modeling of fluid flow and heat transfer, with projects including natural convection cooling spent nuclear fuel storage casks, mixing of nuclear waste, Joule-heated glass melters, induction heated melters for reactive metals, and drag-reducing fairings for drill string risers suspended from off-shore oil drilling platforms. His dissertation research was a model of a supersonic propulsion application using hydrogen-air combustion.

Dr. Perry Meyer is a Staff Scientist in the Fluids & Computational Engineering Group with 18 years experience at PNNL. His academic area of specialization was high speed flow and nonequilibrium thermodynamics. He is an expert in areas of fluid mechanics including jet mixing, gas dynamics, multiphase flow, energy conversion, computational and experimental fluid dynamics, and mathematical modeling. While at PNNL, Dr. Meyer has been a principle investigator on projects relating to jet mixing, safety-related accident and hazard analysis, micro-scale energy conversion, liquid metal magnetohydrodynamics, and aerodynamic testing and design. Dr. Meyer has made significant contributions to the Hanford site in resolving key technical issues associated with tank waste physics and closure of the Tank Waste Safety Issue. Dr. Meyer received a Ph.D. from the University of Washington in 1992 in Aeronautics and Astronautics.

Dr. Yasuo Onishi works at the Pacific Northwest National Laboratory and is an Adjunct Professor of Civil and Environmental Engineering Department, Washington State University. He was a member of the National Academy of Sciences' committee on oil spill and the oil dispersant use, and is an adjunct member of the National Council of Radiation Protection and Measurements. He has conducted field, laboratory flume, and modeling studies of the heated water and contaminants released to surface waters.

Dr. David M. Pfund is a Senior Research Engineer at the Pacific Northwest National Laboratory. He has a Ph.D. (1989) in Chemical Engineering from the University of Oklahoma, where he applied liquid structure theories to the study of solvation in supercritical fluids. At PNNL he applied X-ray, NMR and IR spectroscopies to similar problems. His recent work has focused on the development of anomaly detection methods for low-count gamma sources. He has publications in the Journal of Chemical Physics, the Journal of Physical Chemistry, Langmuir, the AIChE Journal, Ultrasonics, Applied Radiation and Isotopes and the IEEE Transactions on Nuclear Science.

Nodal-Analysis Summary

Dr. Rector is a staff scientist in the Fluid and Computational Engineering group. He has had 30 years of experience in the computational simulation of fluid systems using such methods as lattice-Boltzmann, lattice kinetics and conventional computational fluid dynamics. Dr. Rector is currently involved in the development of computer programs, based on the PNNL developed implicit lattice kinetics methods, for predicting the flow behavior of multiphase systems, most notably the ParaFlow program for large-scale parallel computers.

Mr. Mark Stewart joined PNNL in 2003. His previous work experience has ranged from process simulation at a startup consulting business to process design at a large engineering/construction firm. Although broadly interested in engineering design and analysis, his focus has been the use of computational methods to solve practical problems, particularly involving fluid dynamics and heat transfer. Mark has recently been engaged in the application of the lattice-Boltzmann method to fluid flow through complex geometries.

Mr. Beric E. Wells joined PNNL in 1998 and has participated in and led many Hanford waste storage, mobilization, retrieval and treatment investigations including topics of gas retention and release, waste dilution and jet mixing of chemically reacting Newtonian and Non-Newtonian fluids, and liquid and solid pipeline transport phenomena. He has also investigated Loss of Coolant Accident scenarios for the Nuclear Regulatory Commission. Mr. Wells received both a B.S. and M.S. in Mechanical Engineering from Washington State University.

Dr. Yokuda is a Senior Research Engineer in the Fluid and Computational group at the Pacific Northwest National Laboratory (PNNL). His primary role at PNNL is analysis of both experimental and computational fluid dynamics including multi component and multi phase flow. His experience also includes application of a Monte Carlo N-Particle transport code for radiation detector analysis.