

Review of flow rate estimates of the *Deepwater Horizon* oil spill

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The unprecedented nature of the *Deepwater Horizon* oil spill required the application of research methods to estimate the rate at which oil was escaping from the well in the deep sea, its disposition after it entered the ocean, and total reservoir depletion. Here, we review what advances were made in scientific understanding of quantification of flow rates during deep sea oil well blowouts. We assess the degree to which a consensus was reached on the flow rate of the well by comparing in situ observations of the leaking well with a time-dependent flow rate model derived from pressure readings taken after the Macondo well was shut in for the well integrity test. Model simulations also proved valuable for predicting the effect of partial deployment of the blowout preventer rams on flow rate. Taken together, the scientific analyses support flow rates in the range of ~50,000–70,000 barrels/d, perhaps modestly decreasing over the duration of the oil spill, for a total release of ~5.0 million barrels of oil, not accounting for BP's collection effort. By quantifying the amount of oil at different locations (wellhead, ocean surface, and atmosphere), we conclude that just over 2 million barrels of oil (after accounting for containment) and all of the released methane remained in the deep sea. By better understanding the fate of the hydrocarbons, the total discharge can be partitioned into separate components that pose threats to deep sea vs. coastal ecosystems, allowing responders in future events to scale their actions accordingly.

oil budget | particle image velocimetry | manual feature tracking

The *Deepwater Horizon* oil platform suffered a catastrophic explosion and fire off the coast of Louisiana (Fig. 1) on April 20, 2010, and sank 2 d later. Its blowout preventer (BOP) failed to seal the well, setting off the worst marine oil spill in US history. There were a number of reasons for needing to know the flow rate for the well. First, the optimal design, procedures for execution, or prospects for success of well interventions, such as the coffer dam or top kill, were dependent on flow rate. Second, the amount of dispersant that should be applied by the remotely operated vehicles (ROVs) to minimize an oil slick and release of volatile organic compounds on the surface, where they posed a health hazard to hundreds of workers involved in well intervention, was proportional to the flow rate. Third, the planning for containment of oil at the sea surface while the relief wells were being drilled required a realistic assessment of how much oil needed to be accommodated. Fourth, the rate of depletion of the reservoir, which therefore, determined the final shut-in pressure when the capping stack was closed, depended on the total amount of oil withdrawn. Much discussion by the government science team in Houston immediately after the well was shut in on July 15, 2010, centered on whether the low shut-in pressure was the result of high depletion of the reservoir (exacerbated by

a high flow rate) or the effect of a well that was leaking below the sea floor. Ultimately, the partitioning of the plume in the water column and the impact of the oil on the environment depend on the rate at which the oil is released.

Initially, on April 24, 2010, the US Coast Guard's Federal On-Scene Coordinator, in consultation with BP, estimated that the flow from the well was ~1,000 barrels/d (BPD) (1). On April 28, 2010, the National Oceanic and Atmospheric Administration (NOAA) released the first official flow rate of 5,000 BPD (1). At the time, this number was highly uncertain and based on satellite views of the area of oil on the surface of the ocean. After the public release of videos showing the plume of hydrocarbons escaping from the damaged riser (Fig. 2) in the deep sea on May 12, 2010, many scientists suggested that the flow rate was much higher than 5,000 BPD, although these early estimates from video did not account for the gas to oil ratio as needed to convert total hydrocarbon (gas + oil) flux to oil flow rate. On May 14, 2010, the National Incident Command (NIC) asked its Interagency Solutions Group (IASG) to provide scientifically based information on the discharge rate of oil from the well. In response, the NIC IASG chartered the Flow Rate Technical Group (FRTG) on May 19, 2010. Experts from many scientific disciplines were brought together to perform the FRTG's two primary functions:

(i) as soon as possible, generate a preliminary estimate of the flow rate, and (ii) within approximately 2 mo, use multiple, peer-reviewed methodologies to generate a final estimate of flow rate and volume of oil released.

The results of the FRTG's work are summarized and evaluated for their applicability to accurate and timely estimation of flow rate during an ongoing oil spill incident in the work by McNutt et al. (2). Here, we review the results of flow rate analyses, including work not conducted under the auspices of the FRTG, and place the results in terms of the advancement in scientific knowledge in contrast to contributions to ongoing spill response. We consider not just the best estimates of flow emanating from the wellhead but also how quantifying flow at different locations other than the sea-floor can aid in understanding the fate of oil in the environment.

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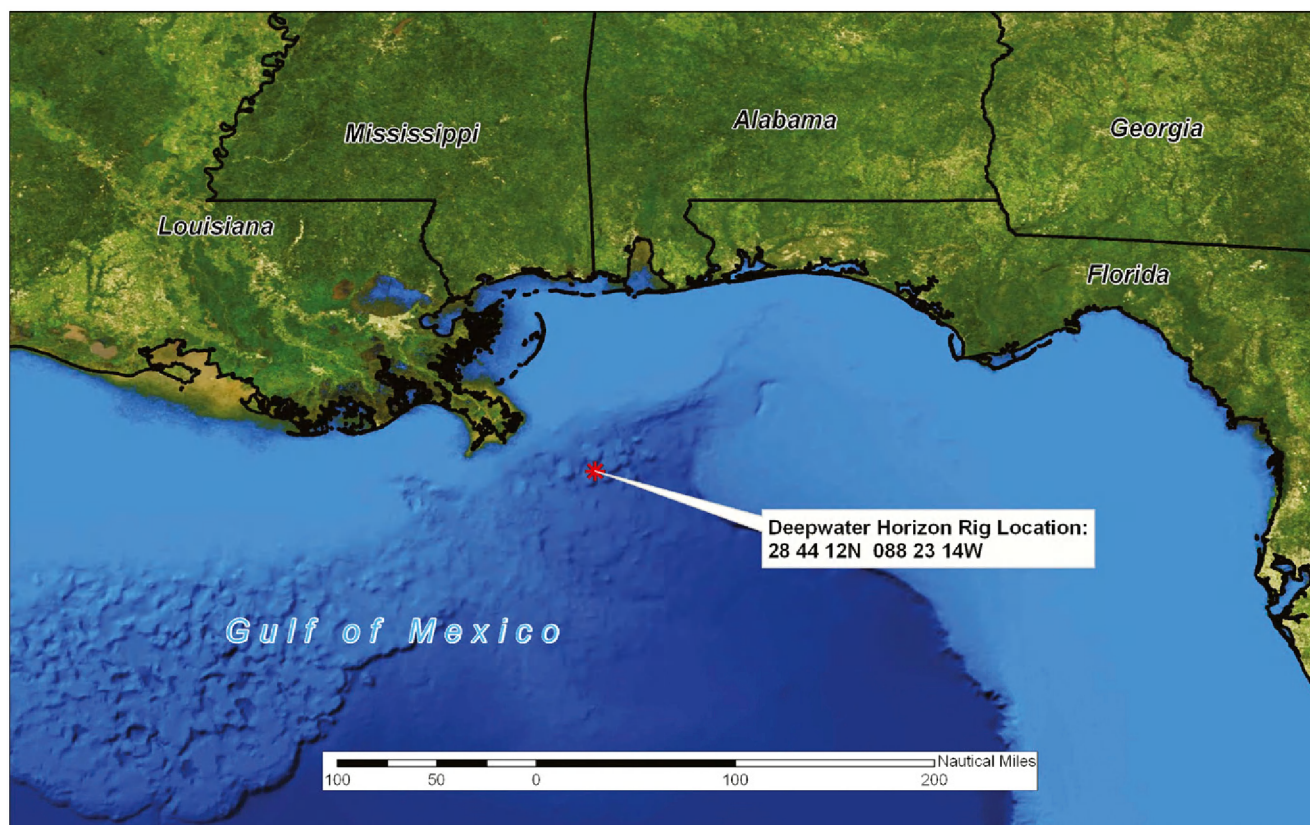


Fig. 1. Location of the Macondo well/Deepwater Horizon spill in the Gulf of Mexico ~50 miles (80 km) southeast of the Mississippi Delta. (Modified from the US Geological Survey).

Flow Rate Estimates from Surface Collection

The flow rate of the Macondo well is a simple concept but surprisingly difficult to measure. The flow from the well consisted of oil plus natural gas, with some of

the gas reacting rapidly with seawater to form methane hydrate. Response workers and the public were primarily interested in the oil fraction, and the charge to the FRTG was to measure the oil discharge but to do so required understanding of how

much of the total flow was oil and how much was natural gas. Obvious methods that might be perfectly sensible for measuring single-phase flow, such as a spinning paddle wheel, would fail because of icing by methane hydrates.

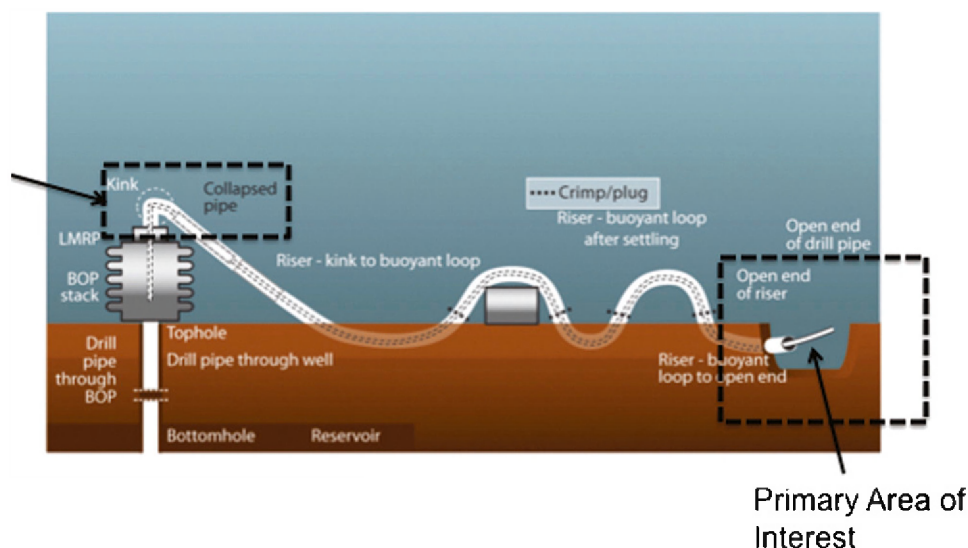


Fig. 2. Schematic diagram of damaged riser at the Macondo well spill site. Most hydrocarbon release occurred in the areas highlighted by black rectangles, emanating from the kink in the riser immediately above the blowout preventer (BOP) stack and the open end of the riser/drill pipe before June 3 and through the lower marine riser package (LMRP) after the damaged riser was cut away.

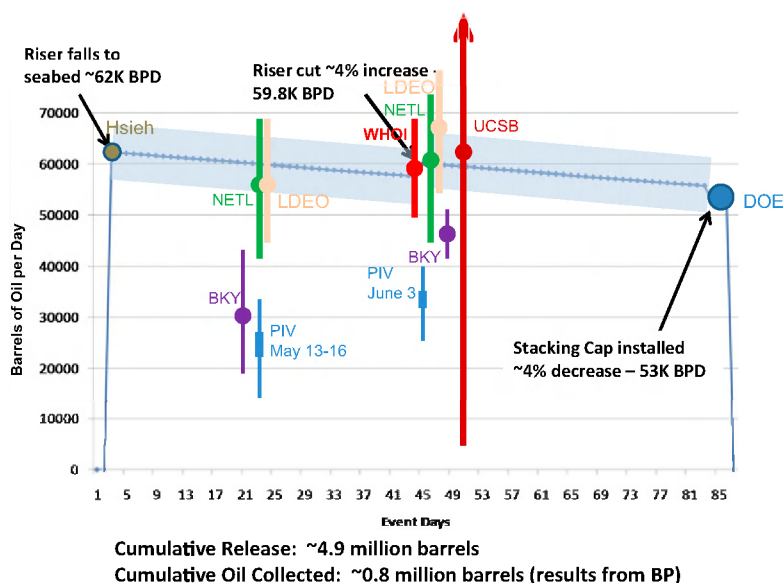


Fig. 4. Summary of flow rate estimates from Table 1. The continuous curve represents the August model for the evolution in flow rate throughout the oil spill incident obtained by extrapolating the 53,000 BPD estimate from DOE at the time that the capping stack was closed (12) back to the beginning of the incident using the reservoir depletion model of Hsieh (13). In this extrapolation, a flow rate increase of 4% was estimated to have occurred when the riser was severed, and a decrease of 4% was estimated when the capping stack was installed. The stippled band represents a $\pm 10\%$ uncertainty in the August flow rate model. Compared with this August model are flow rate estimates from in situ ocean data plotted as a function of the day that the data for that flow rate were collected. Flow rates were typically reported at later dates. The postriser cut estimates all used data obtained on event day 45, but they are slightly offset from each other in time for ease of viewing. The upper bounds of the postriser cut UCSB estimate is shown as an arrow where it goes off the chart. The PIV estimates from the various sources are pooled together, with the thick part of the bar showing the range of the means and the thin part showing the range of the SD.

The National Energy Technology Laboratory (NETL), University of California at Berkeley and University of California at Santa Barbara (UCSB) experts adopted various forms of manual feature-tracking velocimetry (FTV). Manual FTV was performed by visually detecting the displacement of easily recognizable features, such as vortices and eddies, between consecutive video frames. Presumed methane hydrates, bright white particles against a dark jet background, were also easily recognized and tracked. Although there were some minor variations in the manual FTV technique applications (details in appendices in ref. 6), all experts measured similar jet velocities. After jet velocities were measured with manual FTV, volumetric flow rate was determined by multiplying the measured jet velocity times the cross-sectional area of the jet, with appropriate corrections for the gas to oil ratio (GOR). Because measurements were made close to the jet exit (within five jet exit diameters), the radial profile of average jet velocity could be assumed to be uniform and constant (top hat profile).

The work by Crone and Tolstoy (8) used optical plume velocimetry (OPV), a method that was developed and calibrated using laboratory simulations of turbulent

buoyant jets (5). In this method, the image velocity field is established by cross-correlating time series values of image intensity from pixel pairs separated by some distance in the direction of flow. The flow rate was then calculated from the image velocity field using an empirically derived shear-layer correction factor.

The PIV analyses performed by experts A, B, C, and E (Table 1) agreed with each other but produced flow rate estimates that were about one-half the magnitude estimated by the other methods, even using the same primary video observations (6). Other research teams also tried to use PIV but determined that it was not producing reliable fluid velocities in this application. For example, Crone and Tolstoy (8) cite experiments completed before the Macondo crisis (5), showing that PIV would underestimate flow rates by about a factor of two when applied to turbulent buoyant jets. Savas (6) carried out a systematic image velocimetry study of using sections of video where the drifting motion of the ROV camera caused an apparent displacement/velocity of the riser flange. The results showed that PIV software was able to correctly measure the motion of the riser flange only when large interrogation windows were used. For a wide range of interrogation window sizes, PIV software erroneously yielded random values of velocity. The work by Shaffer et al. (9) points out that PIV is a laboratory technique applied under carefully controlled conditions to map the motion of particles a few pixels in diameter in a transparent fluid. At Macondo, PIV software was applied to measure the velocity of transient opaque features from 1 to 500 pixels.

The relatively poor performance of PIV in this particular application thus had several potential causes. Automatic PIV analysis software may be confused by rotating flow structures, can lock on to separated or smaller flow features that are moving more slowly and/or not sampling deeper parts of the flow, and can alias turbulent flow, because correlation window sizes are typically fixed, whereas flow structure sizes are not (5, 6). All of these issues can bias velocity estimates lower and artificially reduce flow rate estimates. More details on how the case was made to discount the PIV estimates in this application are provided in [SI Text](#). The manual FTV method overcame the problems of PIV by using the human brain as an expert system to painstakingly choose large and fast structures to track. OPV inherently avoids many of the problems associated with spatial cross-correlation techniques. Thus, as work on this problem progressed during the crisis, it became clear to many that, although PIV software can correctly analyze videos

Table 1. Flow rate estimates from in situ observations

2010 Date event day	Method	Flow rate (1,000 BPD)	Source
Preriser cut estimates			
May 13–16 ED 24–27	Large eddy tracking	30 ± 12	Berkeley (BKY) (6)
May 13–16 ED 24–27	Particle image velocimetry	23 ± 9	Expert E (6)
May 13–16 ED 24–27	Particle image velocimetry	25 ± 8	Experts A, B, C (6)
May 13–16 ED 24–27	Feature tracking velocimetry	55 ± 14	National Energy Technology Laboratory (NETL) (6)
May 14 ED 25	Optical plume velocimetry	56 ± 12	Lamont–Doherty Earth Observatory (LDEO) (8)
May 31 ED 42	Acoustic Doppler velocity + sonar	57 ± 10	Woods Hole Oceanographic Institution (WHOI) (11)
Postriser cut estimates			
June 3 ED 45	Large eddy tracking	46 ± 4*	Berkeley (BKY) (6)
June 3 ED 45	Particle image velocimetry	35 ± 5*	Expert E (6)
June 3 ED 45	Particle image velocimetry	32 ± 8*	Experts A, B, and C (6)
June 3 ED 45	Digital image velocimetry	62 ± 58*	University of California at Santa Barbara (UCSB) (6)
June 3 ED 45	Feature tracking velocimetry	61 ± 15*	National Energy Technology Laboratory (NETL) (6)
June 3 ED 45	Optical plume velocimetry	68 ± 14	Lamont–Doherty Earth Observatory (LDEO) (8)

All rates expressed in stock tank barrels (stb = 0.159 m³) at the ocean surface for consistency.

*Rates from p. 15 in ref. 6. In some cases, mean and SD values were not identical to values in the appendices of ref. 6, which were finalized after official flow rates were publicly reported.

taken under certain conditions, it was not well-suited for analysis of ROV videos of uncontrolled opaque turbulent oil jets.

Table 1 and Fig. 4 also include the flow rate of a WHOI team (10) derived from

acoustic Doppler current profiler measurements (ADCP). They collected time series measurements over periods of minutes using an imaging sonar to determine the cross-sectional area of the plume at

the end of the riser and the jets at the kink (Fig. 2) and the ADCP to measure the tens of thousands of individual velocities within the flow field. The flow velocity and area estimates were then multiplied to produce an ensemble estimate of the total volumetric flow rate (oil plus gas) of 0.25 m³/s. This approach had the benefit of mapping the interior of the entire hydrocarbon plume acoustically despite the fact that it is opaque to video images. On June 21, 2010, the WHOI team returned to the field with a high-pressure sample bottle and gathered 100 mL uncontaminated discharge of hydrocarbons inside Top Hat #4 as they exited the well. Chemical analysis of this sample revealed that the fluids were by mass less than 1% carbon dioxide and nitrogen, 15% methane, 7% ethane through pentanes, and 77% hexanes and higher petroleum hydrocarbons (11). This detailed understanding of the fluid composition enabled calculation of the volumetric oil and gas fractions under varying temperature, pressure, and phase conditions encountered during their initial transport through the water column (11). This sample became the basis for the oil ratio = oil/(gas + oil) = 0.41 used by the various experts, consistent with previous indications that a value of ~0.4 was appropriate (6). Given the very dissimilar nature of the acoustic vs. video observations, the different methods of analysis, and the independent sources of error, the fact that the flow rates from the WHOI acoustic measurements (Fig. 4) agree with those rates derived from video is exceptionally strong evidence that, in late May/early June, the flow rate of the Macondo well was ~60,000 BPD.

Flow Rate at Well Shut in

Additional estimates of the flow rate were derived when the well was shut in for the well integrity test on July 15, 2010. The mechanism for shutting in the well was to close off the flow with a three-ram capping stack that was mated with the upper flange of the LMRP on the top of the BOP. Government scientists in Houston had requested that the capping stack be equipped with redundant pressure gauges. When the choke valve in the capping stack was throttled back in a series of precisely controlled steps to close off the well, pressure readings from the capping stack taken at the time were analyzed by three separate Department of Energy (DOE) laboratories to yield very consistent results for the flow rate of the well at the time of shut in: 53,000 BPD (12). When combined with a US Geological Survey (USGS) model for reservoir depletion as a function of time (13), these postshut-in results provided flow rate estimates for the entire duration of the oil spill that can be compared against the observations

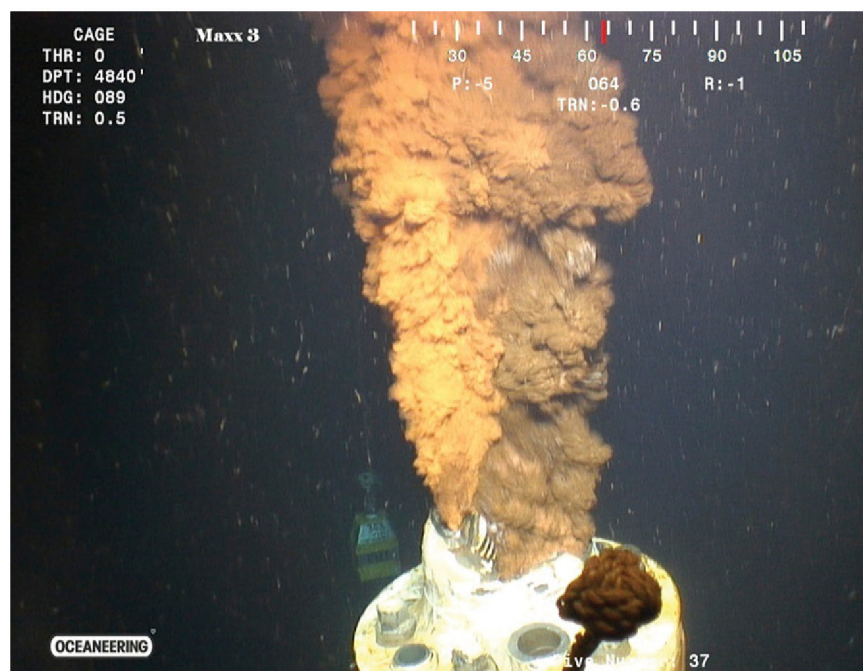


Fig. 5. Hydrocarbons (oil and natural gas) escaping from the end of the riser tube after it was severed on June 3 immediately above the Macondo well BOP stack. (Modified from BP video from ROVs.)

taken during the ongoing incident. Additional details on these calculations are provided in *SI Text*. Based on this analysis, the Department of Interior and DOE released, on August 2, 2010, a time-varying flow rate for the well as a function of time (Fig. 4) that was estimated by the team of scientists from government and academia to be accurate to $\pm 10\%$ (12). Although this figure does not represent a formal statistical error estimate, it approximately accounts for errors in the pressure readings (based on the two redundant pressure gauges) and unmodeled multiphase effects (12). Including discontinuities to account for changing resistance at the well head (i.e., removal of riser or addition of capping stack), the flow rate was estimated to have decreased from 62,000 to 53,000 BPD over the 86 d of the incident for a total release of ~ 5 million barrels of oil. Subtracting the $\sim 800,000$ barrels of oil that never reached the environment because of BP's containment efforts (3) would yield 4.2 million barrels of oil released to the ocean and atmosphere. We call this the August model to correspond to the release month of the estimate and distinguish it from earlier FRTG flow estimates. The other observed flow rates reported here, except as noted, were calculated in a blind manner, without knowledge of the August model. The agreement between this model and the observations of in situ flow in Fig. 4 provide sound evidence that the Macondo well flowed between 70,000 and 50,000 BPD.

Scientific Contributions from Modeling

A number of teams were involved in reservoir and well modeling exercises, some concentrating on modeling the evolution of the producing reservoir at 18,000 ft (5,500 m) below sea surface and others working on the various possible flow paths up through the well and the behavior of the fluids on ascent. Unlike the previous approaches, these teams did not require access to the field or new data acquisition. However, they did gain access to industry proprietary data to constrain model parameters (for example, fluid and reservoir properties, well casings and liners, etc.).

Five DOE national laboratories (Los Alamos, Lawrence Berkeley, Lawrence Livermore, NETL, and Pacific Northwest) independently calculated the flow from the top of the reservoir (representing the reservoir response as a bottom hole pressure) to the release point at the sea floor (14). A statistical sampling method was used with these independent estimates to develop a set of pooled estimates of flow that allowed detailed assessment of flow conditions as related to a variety of factors in the reservoir and the engineered part

of the system (wellbore, BOP, riser, etc.). As shown in Table 2, there was a large spread in the 95% confidence interval in their flow rates for two key time periods, but the best estimate was very close to the August model. The large range in possible flow rates stemmed from uncertainty whether the flow through the well was primarily inside the casing or in the annular space outside the casing (Fig. 6), with the latter flow scenario resulting in significantly lower estimates of flow. One rather significant contribution from modeling was the capacity to consider the effect of restrictions in the BOP on flow rate (15). After the BOP was recovered from the seafloor, a postincident investigation was conducted to determine what could be concluded about the functioning of the various rams in the BOP system. One finding was that the blind shear rams had, at some point, deployed, forming at least a partial restriction to flow through the BOP. Oldenburg et al. (15) modeled the behavior of flow of oil and gas in the reservoir and up through the well as a function of the resistance in the BOP as parameterized by the unknown pressure at the bottom of the BOP (P_{BOP}), which is the top of their model reservoir–wellbore system. They found effects of phase interference of gas and oil that were unanticipated such that oil flow rate is independent of the restriction in the BOP until P_{BOP} equals about 6,600 psia (45 MPa), the pressure above which no gas exsolves (i.e., the Macondo hydrocarbons are single phase). Although a P_{BOP} larger than 6,600 psia would imply that flow is restricted in the BOP, estimation of the precise degree of restriction for any assumed P_{BOP} is complicated because of the strong interplay between pressure and gas exsolution in the whole system (reservoir–well–BOP) (15).

Three independent groups of researchers in the field of reservoir simulation calculated the rate at which oil and gas can be produced from the sands penetrated by BP's Macondo well (16). The reservoir geometry was prescribed by maps generated from 3D seismic data interpreted by the Bureau of Ocean Energy Management (BOEM) geophysicists. The models were constrained using Macondo reservoir rock

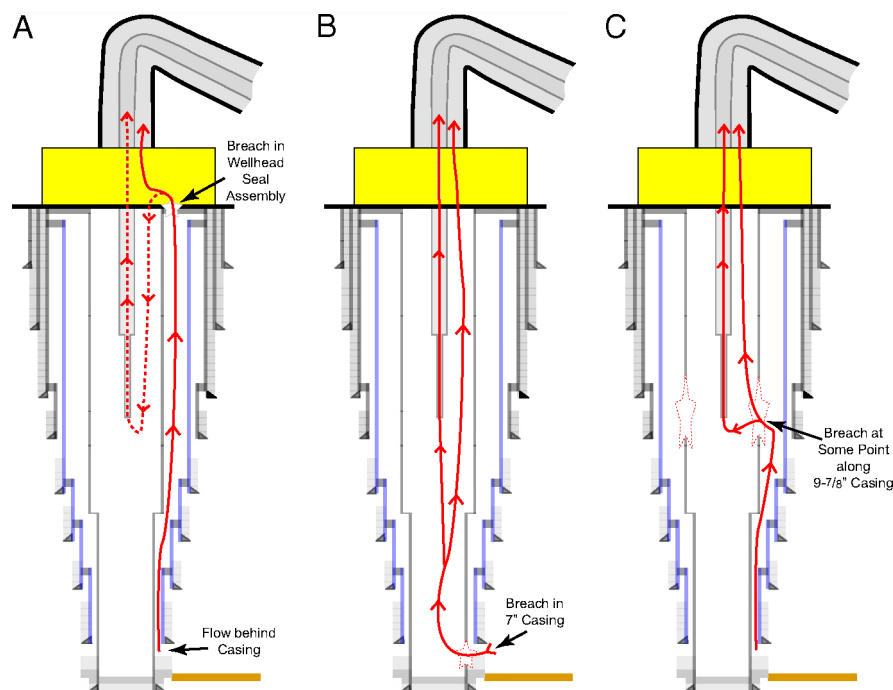
and fluid properties derived from open-hole logs, pressure transient tests, pressure, volume, and temperature measurements, and core samples as well as reservoir data from an analogous well drilled 20 miles (32 km) away. The researchers populated computer models and determined flow rates from the targeted sands in the well as a function of bottom-hole pressure. This modeling provided an estimate of the rate at which oil could theoretically flow into the well. Permeability assumptions significantly impacted the results. In addition, the particular flow path through the well was as important as any reservoir parameter in determining the final flow rate. Because of time constraints, the modelers concentrated on two scenarios: the maximum flow (worst case) conditions and the most likely flow scenario. The results are summarized in Table 3. Two of three groups determined most likely flow rates that were excellent matches to the August flow model. Although the reservoir modeling results were not available early enough to impact the oil spill response in any substantive manner, the well did not need to be flowing to conduct the model simulations. Therefore, theoretically, these flow rates could have been produced before the *Deepwater Horizon* accident. Based on the success of this approach, BOEM is using reservoir modeling to calculate worst case discharge as part of permit conditions before wells enter production, and therefore, some estimate of flow rate would be available should a subsea blowout occur.

Apparent Flow at Ocean Surface

Two teams provided estimates of flow from the Macondo well at the ocean surface using unique approaches. A USGS/National Aeronautics and Space Administration team deployed the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) from an ER-2 research aircraft to quantify both the area and thickness of oil on the ocean surface on May 17, 2010. This instrument had previously been used in such ground-breaking applications as the detection of asbestos in the rubble of the World Trade Center Towers (17). Depending on the aggressiveness with which the team members interpreted the

Table 2. Flow rate estimates from DOE National Laboratory models of flow through well

Date (2010)	95% confidence interval for flow rate (1,000 BPD)	Best estimate for flow rate (1,000 BPD)	August model flow rate (1,000 BPD)
April 25 to May 5	40–91	65	56–67
June 1–3	35–106	70	55–65



and the lower bound on the total Macondo well flow-rate data (2) yields an extreme lower bound on the flux of oil into the deep sea of 29,600 BPD. Taking the upper bound on the Macondo well flow rate and the lower bound on the P3 data yields the maximum flux to the deep sea: 44,800 BPD. The most likely value is about 33,000 BPD or approximately one-half of the total Macondo oil flux remaining in the deep sea. The NOAA results also confirm that the methane remained in the deep sea (20). The net result, therefore, of this deep sea release is a very substantial fraction of the total hydrocarbon budget being absorbed in the deep ocean: one-half of the oil and essentially all of the methane. These values also imply that the oil flux to the surface on May 17, before BP's containment efforts, would have been ~24,000–30,000 BPD, thus explaining the lower values derived from the AVIRIS measurements without needing to assume that much of the oil had been missed in the form of thick oil or tar balls.

Conclusions

The following scientific understanding will better prepare scientists and the oil spill response community for future deep sea blowouts.

- i) The method of automated PIV, used by several groups of experts during the spill to analyze video segments, was inappropriate for this application and resulted in oil flow rates that were biased too low by a factor of two.
- ii) Except for the PIV estimates, there is remarkable agreement for the discharge rate for the well, regardless of whether the estimate was derived from ROV video, acoustic Doppler data, pressure measurements during well shut in, reservoir modeling, or trends in gas to oil ratio during surface collection. Flow rates fall between 50,000 and 70,000 BPD.
- iii) These estimates do not require but do not preclude a modest reduction in

flow rate over time, which might be caused by reservoir depletion.

- iv) Modeling also proved to be an extremely valuable exercise in terms of providing insight to the likely effect of the deployment of the blind shear rams and suggesting that modeling be used as a tool that can assess the impact of future spills before they happen.
- v) Estimates of flow rate at the ocean surface derived from multispectral imaging of oil on the ocean surface and chemical sensing of the hydrocarbons evaporating off the ocean surface coupled with the total flow rate from the well indicate that ~50% of the oil (>2 million barrels) and essentially all of the methane did not reach the ocean surface.

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