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 seafloor can aid in understanding the fate of oil in the environment.

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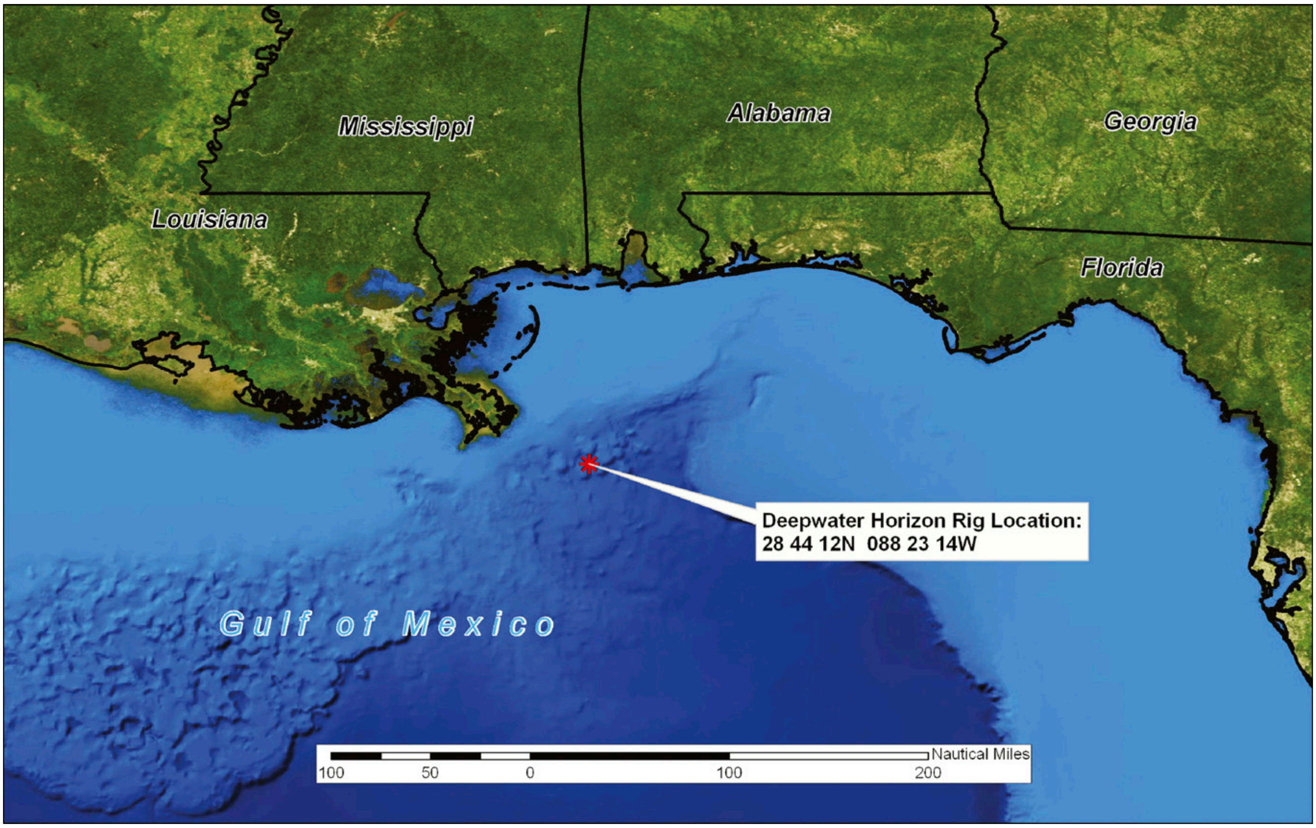

Fig. 1. Location of the Macondo well/*Deepwater Horizon* spill in the Gulf of Mexico ∼50 miles (80 km) southeast of the Mississippi Delta. (Modified from the US Geological Survey).

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.

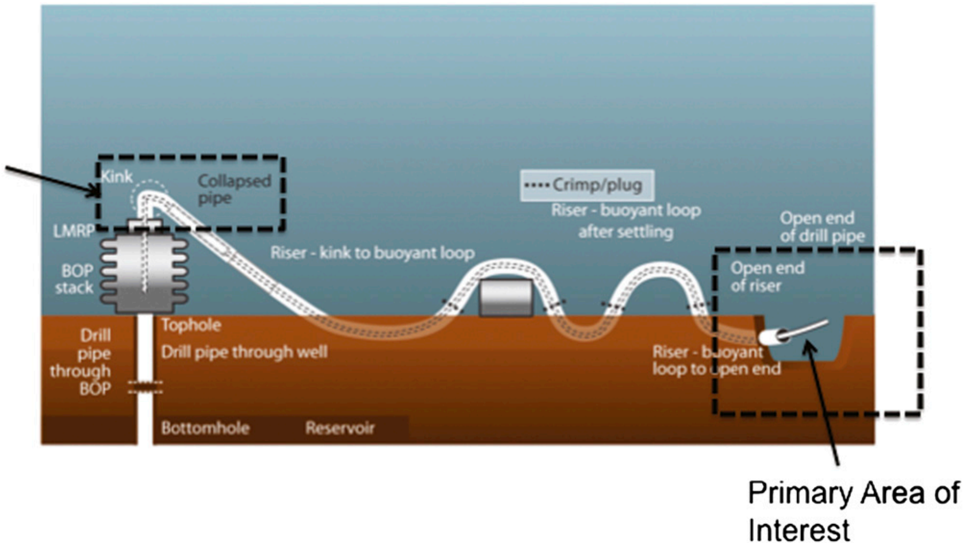

Fig. 2. Schematic diagram of damaged riser at the Macondo well spill site. Most hydrocarbon release occurred in the areas highlighted by black rectangles, emanating from the kink in the riser immediately above the blowout preventer (BOP) stack and the open end of the riser/drill pipe before June 3 and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

BP was working up until the well was finally capped to muster enough capacity to contain all of the flow on surface ships, which would have provided an excellent final measure of flow rate (at least at that one point in time). By mid-June, BP was collecting 25,000 BPD of oil through two containment systems: a riser to the vessel *Discoverer Enterprise* and the choke line to the *Q4000* semisubmersible (3). Video showed that a substantial amount of oil was still discharging into the ocean, and therefore, this rate provided only a lower bound on the flow rate for the well. Tropical storms delayed BP's plans to deploy additional containment systems before closure of the well through the capping stack on July 15, 2010.

Even with only partial surface containment, Camilli (described in ref. 2) devised a method using gas to oil ratios of hydrocarbons recovered to the surface for estimating the total flow of the well (Fig. 3). The apparent gas to oil ratio of the flow collected at the surface (3) indicates a relatively larger gas component than the flow from the subsurface well, because the riser from the wellhead to the ship seemed to act as a separator, preferentially siphoning the lighter components to the surface in the case of incomplete capture. As the collection approaches 100% of total flow in this extrapolation, the gas to oil ratio must trend to the true value at the seafloor, which was obtained with a pressurized sampling bottle deployed from an ROV by Woods Hole Oceanographic Institution (WHOI). This method of estimating flow rate is not highly precise on account of both the scatter in BP's collection data and the need to extrapolate the line some distance outside the region of the data, but it yields a flow rate of 48,000–66,000 BPD (2) corresponding to the time of sample collection on June 21, 2010.

Flow Rate Estimates from in Situ Observations

At the time of the *Deepwater Horizon* blowout, there were no proven methods for directly measuring the deep sea discharge of hydrocarbons at the relevant pressures and temperatures. Oceanographers had experience in quantifying flow rates from deep sea hydrothermal vents at midocean ridges (4, 5), but methods developed from those environments had not previously been applied to mixtures of oil, gas, and water. Thus, a variety of approaches were pursued. Table 1 summarizes the flow rates that were obtained from acoustic and video observations in the deep sea, and Fig. 4 plots those flow rates as a function of the event day (ED) (Table 1, ED) of the measurement. Rates are given for two key flow periods: before severing the sunken riser (Fig. 2), which had been left in place to aid in the Top Kill procedure, and after severing the riser (Fig. 5). The flow geometry before severing the riser was more complex, because in addition to a large plume emanating from the end of the riser, several jets of oil and gas were escaping from tears in the kink in the collapsed pipe at the top of the lower marine riser package (LMRP). After the riser was severed, all discharge flowed through the top of the LMRP.

The majority of the flow rates from independent teams listed in Table 1 and shown in Fig. 4 relied on underwater video of hydrocarbon plumes taken by ROVs as the primary data for assessing the flow of the Macondo well. The video data examined were either opportunistic from work-class ROVs working in and around the incident site or specifically commissioned by the FRTG to be collected by an ROV for flow rate analysis. In all of these cases, an oil volume fraction [i.e., oil/(gas + oil)] of ~0.4 was assumed based on early time series analysis of video showing alternating oil vs. gassy discharge when humps and cooling in the riser (Fig. 2) caused the flow to separate (6).

Several expert teams used a flow visualization and measurement technique

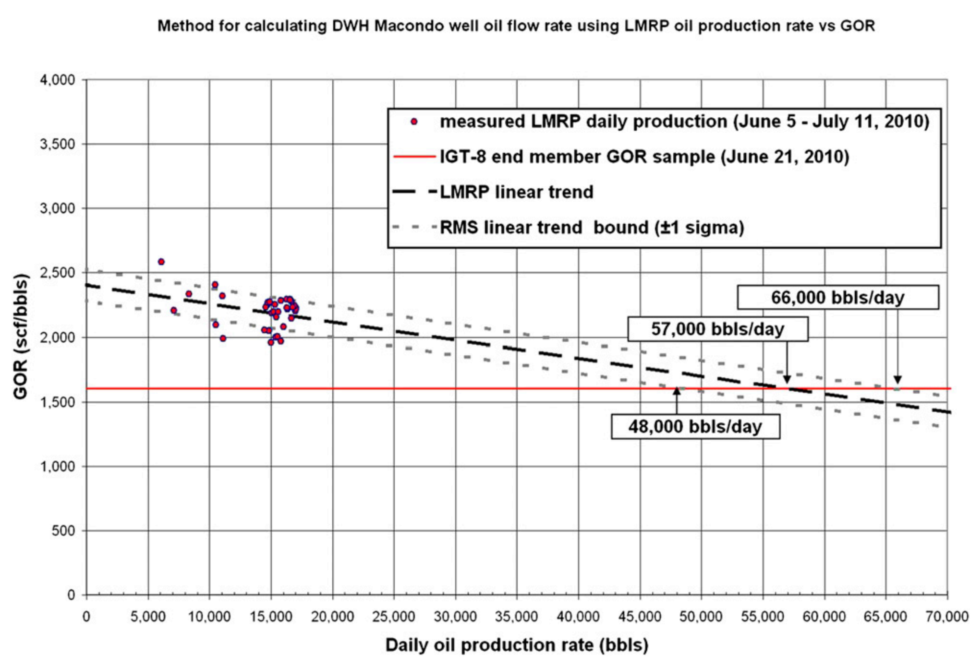

Fig. 3. Daily averages of GOR as a function of oil produced. The general trend indicates that the GOR drops as a greater percentage of the total flow is produced to the surface but with considerable scatter. If the entire flow was captured, the GOR would match the true GOR of the well. The horizontal line at a GOR of 1,600 is equivalent to the surface GOR of the IGT-8 sample taken by WHOI on June 21, which was obtained at the point of exit at the wellhead and is taken to represent the true GOR of the Macondo reservoir fluids escaping from the well. Assuming that GOR samples acquired at the surface would trend linearly to the actual GOR (IGT-8 sample collected by WHOI at well head), then the intercept should indicate the total oil flow rate on June 21. The best-fitting linear trend to the GOR data as a function of surface oil yield indicates that, if BP had been able to capture the total flow at a GOR of 1,600, then the oil captured would have been 57,000 BPD on June 21. The 1 SD uncertainty on the best-fitting line to the GOR data allows the flow rate at the GOR of 1,600 to be between 48,000 and 66,000 BPD. (Modified from ref. 2.)

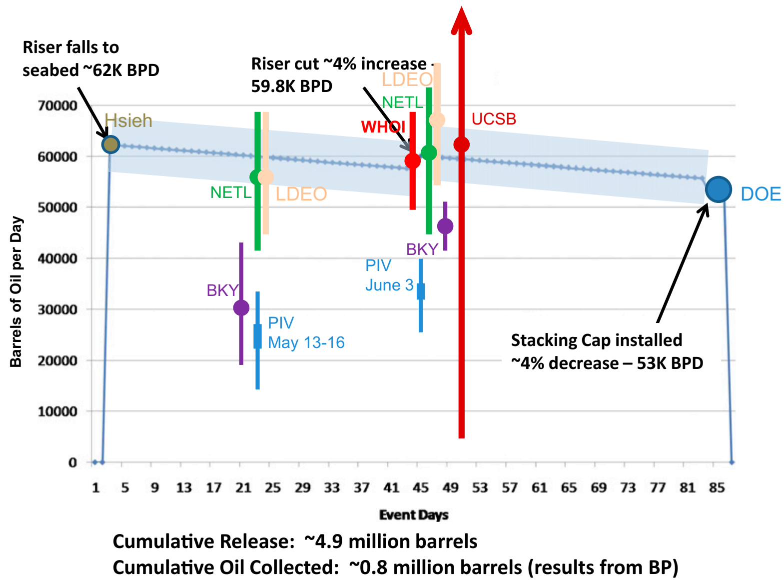

Fig. 4. Summary of flow rate estimates from Table 1. The continuous curve represents the August model for the evolution in flow rate throughout the oil spill incident obtained by extrapolating the 53,000 BPD estimate from DOE at the time that the capping stack was closed (12) back to the beginning of 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 ±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 postrise 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.

called particle image velocimetry (PIV) to estimate the velocity of the outer surface of oil leak jets. PIV was originally developed as a laboratory technique to measure a 2D velocity field in a transparent gas or fluid illuminated with a thin sheet of laser light (7). To see the motion of the transparent gas/fluid, seed particles small enough to follow the fluid flow (i.e., with a low Stokes number) are added to the fluid: typically 1–10 μm for gases and 1–100 μm for liquids. A digital camera with line of view normal to the laser sheet records two or more consecutive images of the seed particles. The displacement of particles between consecutive frames gives a 2D velocity vector field. PIV software has been developed to analyze automatically sequences of video frames using cross-correlation analyses of small interrogation windows. In the Macondo application, PIV analysis software attempted to measure the velocity of visible features (vortices, eddies, white particles presumed to be methane hydrates, etc.) on the surface of the opaque oil leak jets. With assumptions for the radial jet velocity profile (typically Gaussian), oil leak rates could be calculated from measured jet surface velocities.

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 m^3) 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 m^3/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.

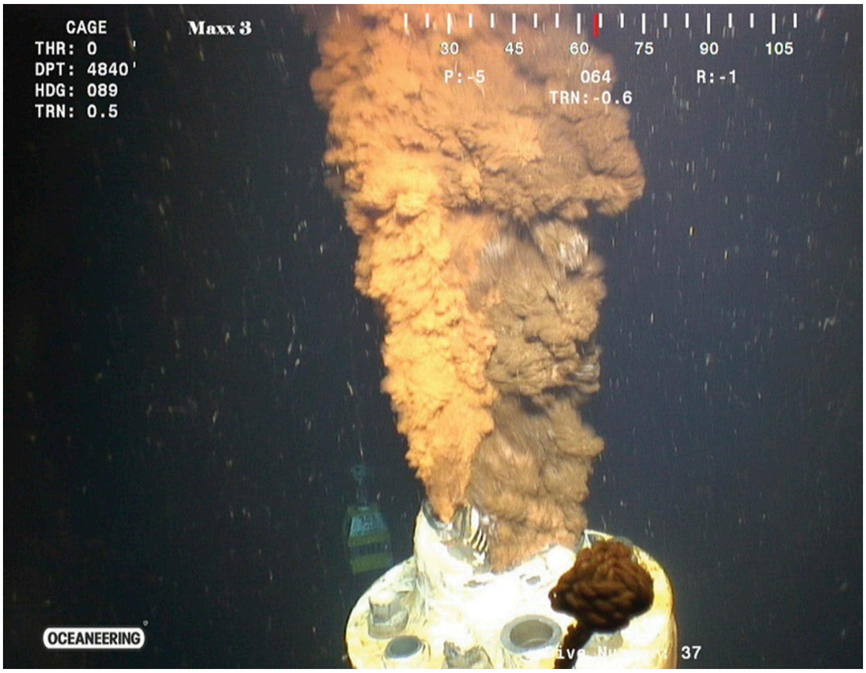

Fig. 5. Hydrocarbons (oil and natural gas) escaping from the end of the riser tube after it was severed on June 3 immediately above the Macondo well BOP stack. (Modified from BP video from ROVs.)

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 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 ±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 ∼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 openhole 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

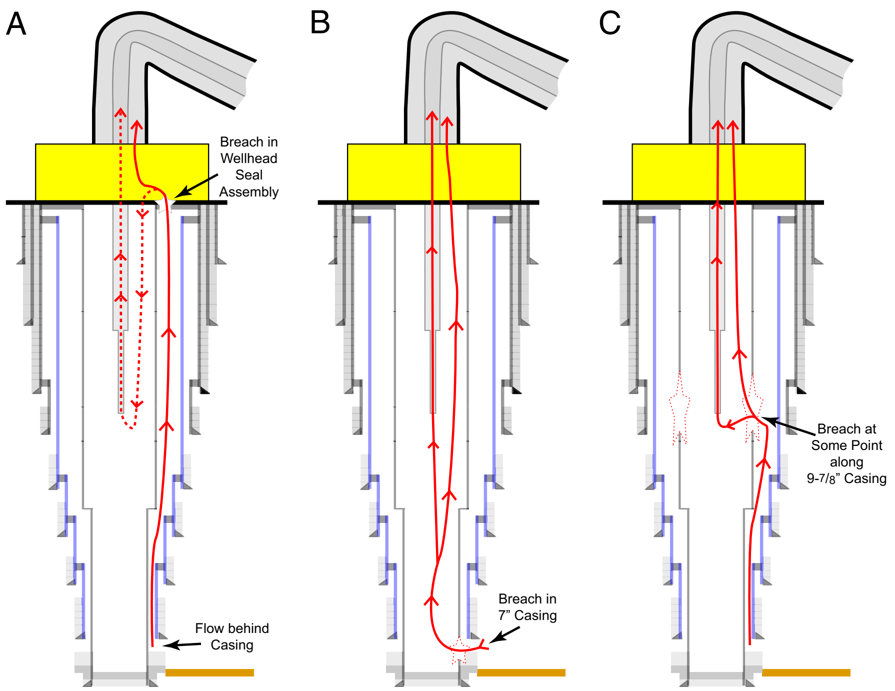

Fig. 6. Schematic diagram of possible well flows modeled by the well modeling teams from the DOE National Laboratories. (*A*) Scenario 1: flow initiates in the annular space between liner and casing, flowing through a breach at the top (in the seal assembly) into BOP and then riser; depending on flow restrictions in BOP, some flow may reenter the 9 7/8-in casing to flow down to enter the drill pipe. (*B*) Scenario 2: flow initiates in a breach of the 7-in casing, flowing up the casing. Some flow enters the drill pipe, and some continues up the casing to BOP. (*C*) Scenario 3: flow initiates in the annular space between liner and casing, entering a breach in 9 7/8-in casing and continuing to flow up inside the casing. Some flow enters the drill pipe, and some continues up the casing to BOP. [Modified from Guthrie et al. (14).]

presence of oil in each pixel imaged on the sea surface, they estimated that the amount of oil on the sea surface on May 17 was between 129,000 and 246,000 barrels (18). They converted these numbers to a lower-bound flow rate by accounting for the amount that had been skimmed and burned according to the US Coast Guard tally (19). They also modeled the likely amount that had been evaporated by assuming that 40% of the oil consisted of volatile components lost to evaporation or dissolution based on available NOAA information. Although a lower bound, their estimate of the flow rate of 12,500–21,500 BPD underestimated the government's final August result by a factor of three, even at the upper bound. Three factors likely contributed to the underestimate. Within a few days of the team's release of their estimate of the Macondo flow rate, the first scientific reports of a plume of oil trapped in the deep sea were publicized. Clearly not all of the flow from the Macondo well was appearing at the ocean surface. A second problem could be a contribution from tar balls. Submerged tar balls are concentrations of oil that are easily missed in the inventory from the air. The third problem is that the near-infrared spectroscopy method of AVIRIS was only able to measure oil up to 4 mm in thickness, but patches of oil at least 2 cm in thickness were observed during the field calibration of the sensor. Clark et al. (18) estimated that the surface oil could have been as much as 500,000 barrels on May 17 on account of failure to accurately measure thick oil.

Table 3. Flow rate estimates from reservoir modeling

Group	Most likely flow rate (1,000 BPD)	Worst case discharge (1,000 BPD)	August model flow rate (1,000 BPD)
Hughes (Louisiana State University)	63 (channel/levee complex)	64 (extensive sheet sands)	62 decreasing to 53
Kelkar (University of Tulsa)*	27–32	37–45	62 decreasing to 53
Gemini Solutions Group	60 decreasing to 50	102 (flow-through multiple paths in well)†	62 decreasing to 53

*Lower Kelkar estimates result from more conservative permeability and flow path assumptions compared with those assumptions adopted by other modeling teams.
†Larger worst case discharge for Gemini team results from considering multiple flow paths through the well, whereas other teams considered only geologic controls on maximum flow.

A NOAA team (20) analyzed airborne atmospheric data obtained from a P3 research aircraft to quantify the amount of hydrocarbons (gas plus oil) evaporating from the *Deepwater Horizon* oil spill. They calculated that ~458,000 kg/day hydrocarbons were evaporating from the ocean surface. Certain volatile organic compounds in the Macondo reservoir fluids, including isomers between 2,2-dimethylbutane and n-nonane, were found in the atmosphere in the same proportion as in the reservoir, suggesting that they were insoluble in seawater and fully evaporated. However, methane, ethane, benzene, toluene, and n-butane were absent or substantially depleted in the atmosphere relative to the reservoir, indicating total to partial removal of soluble species in the water column. Their observations allowed a precise calculation of the percentage of evaporation (14%) and dissolution in seawater (33%) for early June compared with the 40% combined total of evaporation and dissolution assumed by Labson et al. (19) in computing a flow estimate from AVIRIS data. From the insoluble species, it was possible to derive a flow rate for how much of the Macondo oil was surfacing on the date of the flights (June 10, 2010: ~6,200–12,400 BPD). This flow rate assumes that dissolution affected the gas fraction only, which is supported by the data, and an oil/(oil + gas) volume fraction of 0.41. At this time, ~17,000 BPD oil were being collected through Top Hat #4, such that the entire flow of the well was not entering the ocean. This method of measuring the surfacing oil avoids the problem of tar balls but again, does not measure the oil that remains in the deep sea. This estimate of flow was published after the August model was released and therefore, was not an entirely blind analysis. It places only a lower bound on flow rate, because it did not quantify oil that did not surface.

The availability of apparent flow rate estimates at the ocean surface provides an opportunity to estimate the amount of the Macondo flow that did not rise to the surface. Given that the best estimate for full flow of the well from in situ observations on about June 10, 2010 is 59,000 ± 9,000 BPD, subtracting from that flow the collection rate of 17,000 BPD yields a net flux of 42,000 ± 9,000 BPD entering the ocean. Using the upper bound on the surface flow from the NOAA P3 data (20) 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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