Appendix C – Camilli 2010; Woods Hole Oceanographic Institution Acoustics Analysis Report

Camilli, R. 2010. Final Oil Spill Flow Rate Report and Characterization Analysis, Deepwater Horizon Well, Mississippi Canyon Block 252. Woods Hole Oceanographic Institution report to the U.S. Coast Guard. August 10, 2010.

Final Oil Spill Flow Rate Report and Characterization Analysis
Deepwater Horizon well
Mississippi Canyon Block 252

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August 10, 2010

submitted to the
United States Coast Guard
Research and Development Center
contract # HSCG3210CR0020
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Task 3.3; Deliverable #4

The analysis and findings described here were authored by the WHOI Flow Rate Measurement Group: Richard Camilli (WHOI), Andrew Bowen (WHOI), Dana Yoerger (WHOI), Alexandra Techet (MIT), Daniela Di Iorio (UGA), Louis Whitcomb (JHU);along with chemical analyses and documentation by Christopher Reddy (WHOI), Jeff Seewald (WHOI), Sean Sylva (WHOI), and Robert Nelson (WHOI). Additional operations and technical support was provided by Weatherford Pipeline Services, Teledyne RDI, SoundMetrics Corp, and Oceaneering.

Executive Summary:

At the direction of the United States Coast Guard (USCG) Research and Development Center, the Woods Hole Oceanographic Institution (WHOI) was contracted to undertake on-site data collection and analysis of the DEEPWATER HORIZON oil spill. This report has been submitted in fulfillment of USCG contract # HSCG3210CR0020 Deliverable #4. This analysis effort employed acoustic technologies mounted to a remotely operated vehicle (ROV) to directly measure flow rates of oil from the MC252 Deepwater Horizon (Macondo) well. Direct samples of hydrocarbons were collected from within the well riser to determine the gas-oil ratio. Both the flow rate analysis and sample collection were conducted on a non-interfere basis, wherein all operations were performed as time and equipment availability permitted during containment activities at the well site. This provided only a minimum time window to carry out measurement, under less-than optimal measurement conditions.

Flow rate estimates for the riser and BOP were constructed from acoustic Doppler velocity and sonar multibeam cross sectional estimates of each plume. Acoustic measurements were recorded after the top-kill attempt had ended and before the riser was cut, during beginning on May 31, 2010 and extending the early morning hours on June 1, 2010. The ROV was operated by Oceaneering International and supplied by BP. Velocity measurements were recorded at two distinct sites, above the riser pipe and at the kink above the BOP. Flow estimates were derived from three different Doppler velocity view angles above the riser pipe and three Doppler velocity view angles above the BOP during *MAXX*3 ROV Dive #35. Plume cross section measurements were completed using an imaging multibeam sonar on *MAXX*3 ROV Dive #35 and #36.

Hydrocarbon composition was determined based on end member samples collected using isobaric gas-tight samplers integrated onto the Millennium 42 ROV Dive #70. This collection was completed on June 21, 2010, approximately three weeks after the flow measurements. At this time of collection the kinked riser section directly above the BOP had been cut off and the ‘top hat’ containment system had been placed over the riser stub.

The cross sectional area of each plume was integrated with its respective average velocity and then normalized using the measured oil fraction coefficient. Due to the inherently high variability of flow within these turbulent jet plumes, the flow estimates were calculated as average values using ensembles of statistically large sample populations. Over 16,000 Doppler velocity measurements and 2,600 multibeam sonar cross sections were used to calculate the flow rates of these plumes.

Estimated flow rates on May 31, 2010:

Gas-oil ratio:	**56.3% gas and 43.7% oil**
Riser:	**40,700 bbl oil/day**
BOP kink:	**18,500 bbl oil/day**
Total flow rate:	**59,200 bbl oil/day**
Cum well release	**5 million bbls**
Net spill volume	**4.2 million bbls**

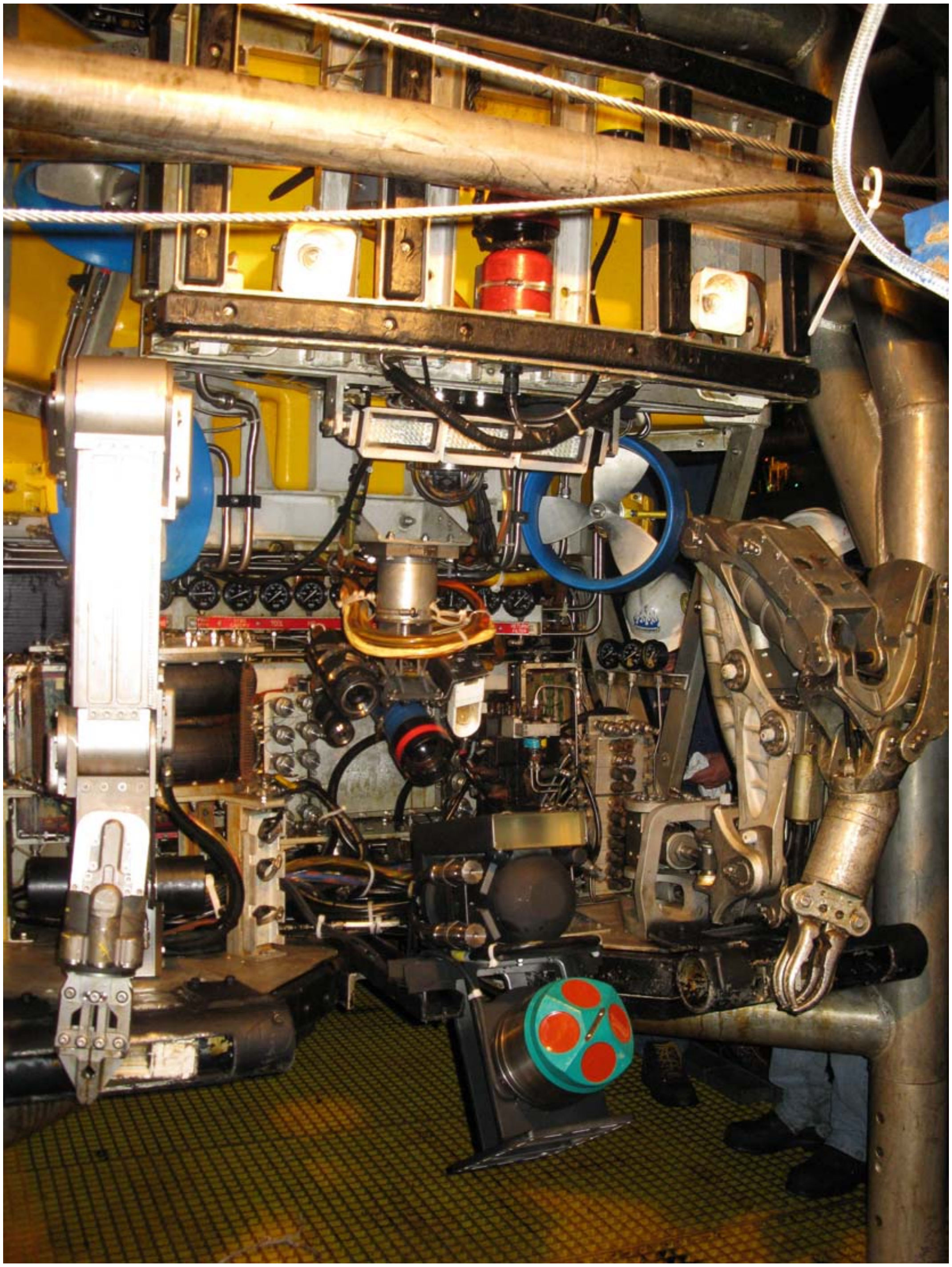

Fig 1: Photo of *MAXX*3 ROV prior to acoustic flow rate survey operations. The ROV is equipped with a forward-looking 1.2MHz ADCP (visible as green object with four red piezo-acoustic disks), and a 1.8MHz acoustic multibeam imaging sonar (visible as yellow rectangular and black circular object directly above the ADCP).

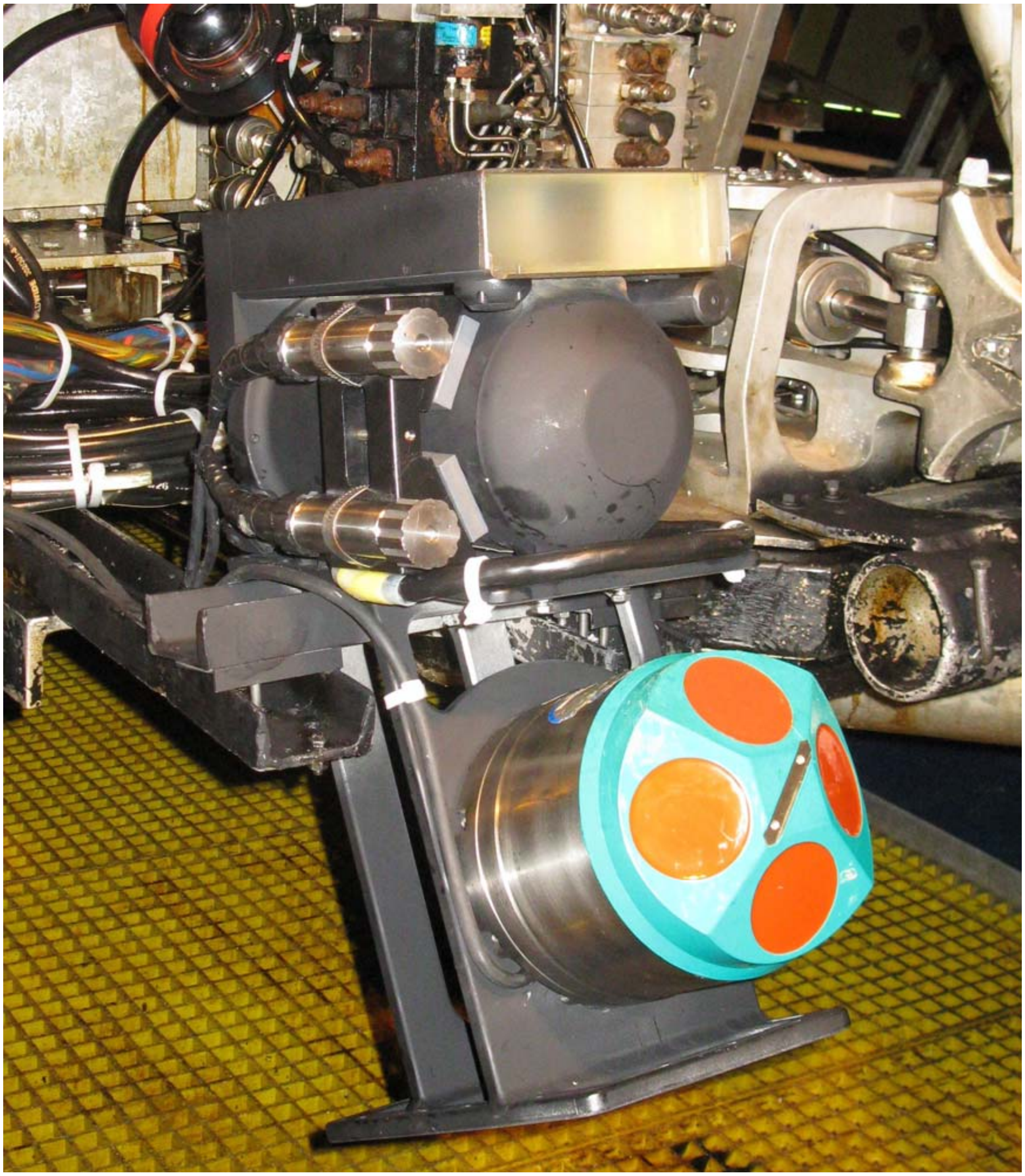

Fig 2: Close-up photo of forward looking ADCP and imaging multibeam sonar mounted on the Oceaneering *MAXX*3 ROV.

ADCP measurements

Flow velocity measurements of the rising plume were obtained with a 1,200 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by Teledyne RD Instruments, San Diego, CA. Figs 1&2 are photographs of the ADCP unit mounted on the *MAXX3* ROV. This instrument measures fluid velocity parallel to each of four independent sonar beams at regular spatial intervals along the length of each beam. This instrument has four independent sonar beams oriented 30° from the instrument axis on a 90° plan. The instrument was mounted on the front of the *MAXX3* ROV with the instrument axis tilted 30° above horizontal. Fig 3 is a drawing depicting the sonar installation showing acoustic beam #4 oriented horizontally, beam #3 oriented 60° above horizontal, and beams #1 and #2 oriented above the horizontal to, respectively, starboard and port.

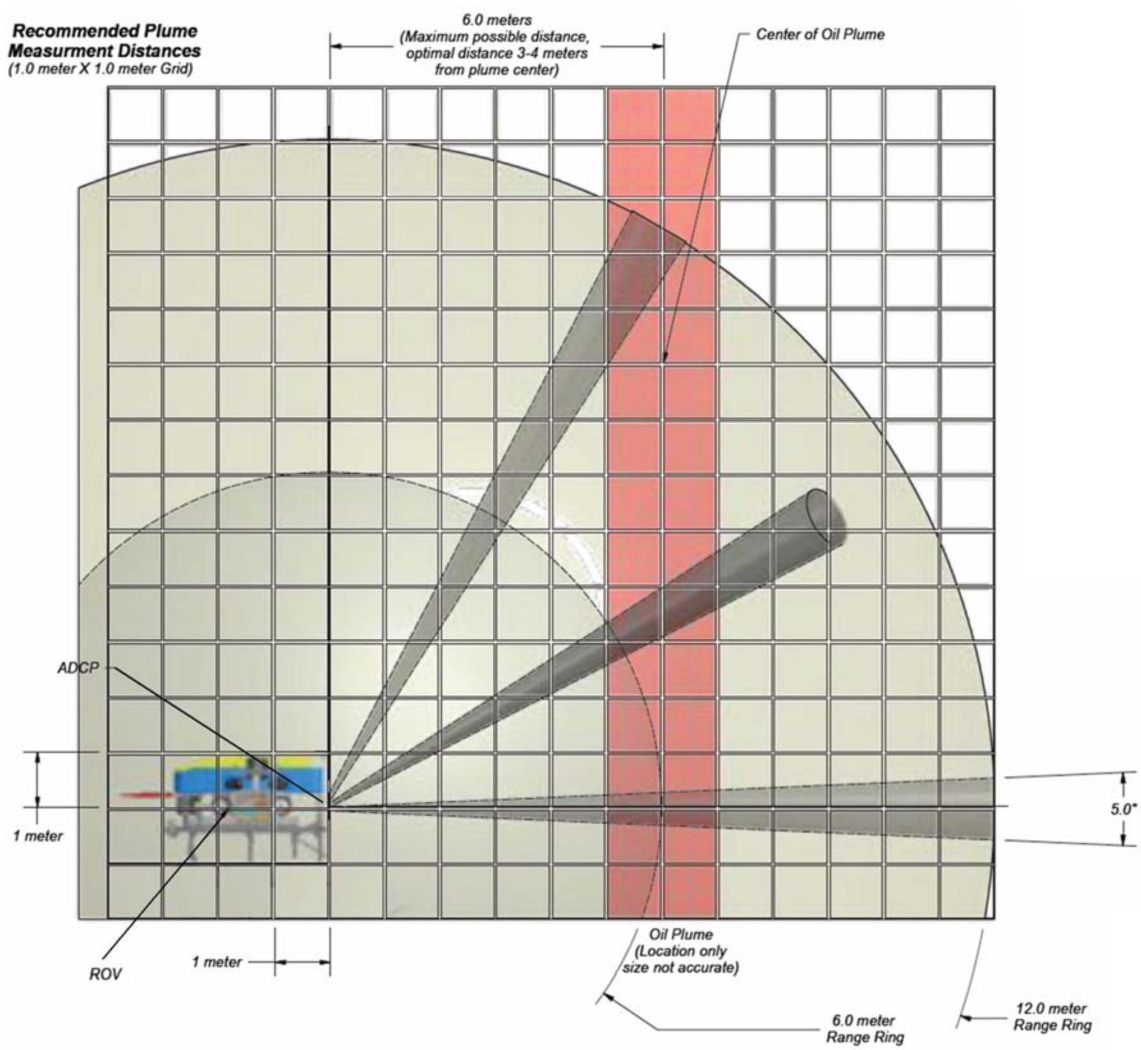

Figure 3: Schematic showing ADCP, as configured on the ROV, with maximum possible beam range at 6 meters offset from plume center.

For the measurements reported herein, the unit was configured to report velocities for each beam at locations up to 15 m from the instrument at fixed intervals along each beam. The ADCP was configured to generate ping ensemble data records at regular interval in several different modes as indicated in Fig 4. The ADCP measurement of the flow velocity along the direction of each beam at each bin interval is specified by the manufacturer to have an expected single acquisition measurement error standard deviation that varies from 9.33 cm/s (for Setup #1) to 2.75 cm/s (for Setup #4 and #5). The expected variation in the measurement standard deviation varies with bin size. Larger bins result in smaller standard deviation but decreased spatial resolution, whereas greater pings per ensemble and greater sample populations result in smaller standard deviation but decreased temporal resolution. For this work the naturally high turbulence of the source plumes made it necessary to use statistically larger sample numbers; thus lower temporal resolution was deemed an acceptable tradeoff for decreased measurement error.

ADCP sonar data of the oil leak plumes at two leak sites: the riser end leak site, and the BOP leak site. At each site, the *MAXX3* ROV was positioned facing the rising oil plume at three locations with the vehicle heading of, respectively, 120º, 240º, and 360º. The lateral ADCP standoff distance from the plume was typically between 2 to 4 m, depending on field of view obstructions. At each station, ADCP sonar data was obtained for durations of approximately 5 minutes in one or more of the configurations given in Fig. The flow velocity data were post-processed and combined with ROV navigation position estimates to compute the instantaneous velocity of each ping ensemble within the 3D coordinate frame. The riser plume velocity measurements used a total of 42,270 ADCP measurements (Fig 5), and the BOP kink plume used a total of 42,894 ADCP measurements as the initial sets of data points. A subset of these velocity measurements (8,372 and 7,763 data points for the riser and BOP kink, respectively) were defined as being within the plume, were then back-projected down to the imaging sonar plane. These back-projected points were then averaged together to produce a time-averaged vertical velocity of the flow at each leak site.

ADCP Setup	Pings Per Ensemble	ADCP Bin Size (m)	Number of Bins	Nearest Bin (m)	Farthest Bin (m)	Ensemble Standard Deviation (cm/sec)	Ensemble Period (sec)
#1	1	0.25	59	0.79	15.29	9.33	1.5
#2	1	0.25	59	0.79	15.29	9.33	1.5
#3	3	0.25	59	0.79	15.29	5.39	1.5
#4	1	0.50	30	1.01	15.51	4.76	0.9
#5	3	0.50	30	1.01	15.51	2.75	0.9

Fig 4: ADCP Configurations

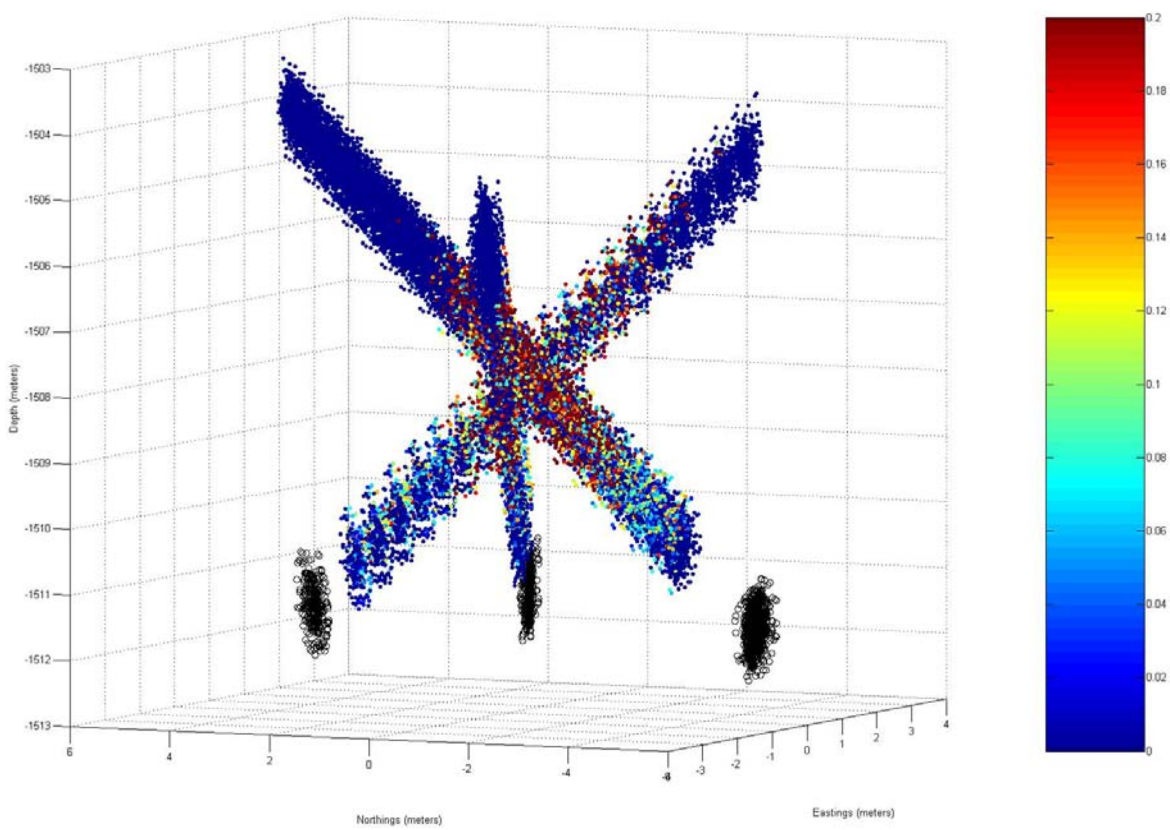

Fig 5: 3D reconstruction of over 42,000 ADCP velocity field measurements recorded at the riser leak site. Each dot represents the location of a Doppler ping ensemble, with the dot color describing the estimated velocity in m/s. The black circles indicate the location of the ADCP instrument during this measurement process.

Acoustic multibeam imaging

Acoustic multibeam imaging was performed at the riser and BOP kink leak sites using a Didson 3000 dual frequency imaging multibeam sonar operating at 1.8MHz. The theoretical resolution at this frequency is on the order of a centimeter. A series of over 1,000 plume cross sections were recorded above each of the leak locations (1089 and 1500 cross sections for the riser and BOP kink, respectively) wherein the sonar imaging plane was positioned at a lateral standoff distance of between 4 and 7 meters, with a height greater than 5X above the source diameter. These sonar cross section measurements were recorded at approximately 7Hz and required between 3 and 4 minutes of acquisition time per leak site.

Cross section calculation was based on inter-frame motion tracking of acoustic returns greater than or equal to 6dB above background noise and areas of plume flow were counted only if the contiguous area was equal to or greater than $100 cm^2$ (Fig 6). Because the sonar was mounted to the ROV with an upward viewing angle of 10º the cross-section estimates were normalized by cosine 10º. The average area cross sections of the leak plumes at the riser and BOP kink were calculated to be $0.87\ m^2$ and $0.61 m^2$, respectively.

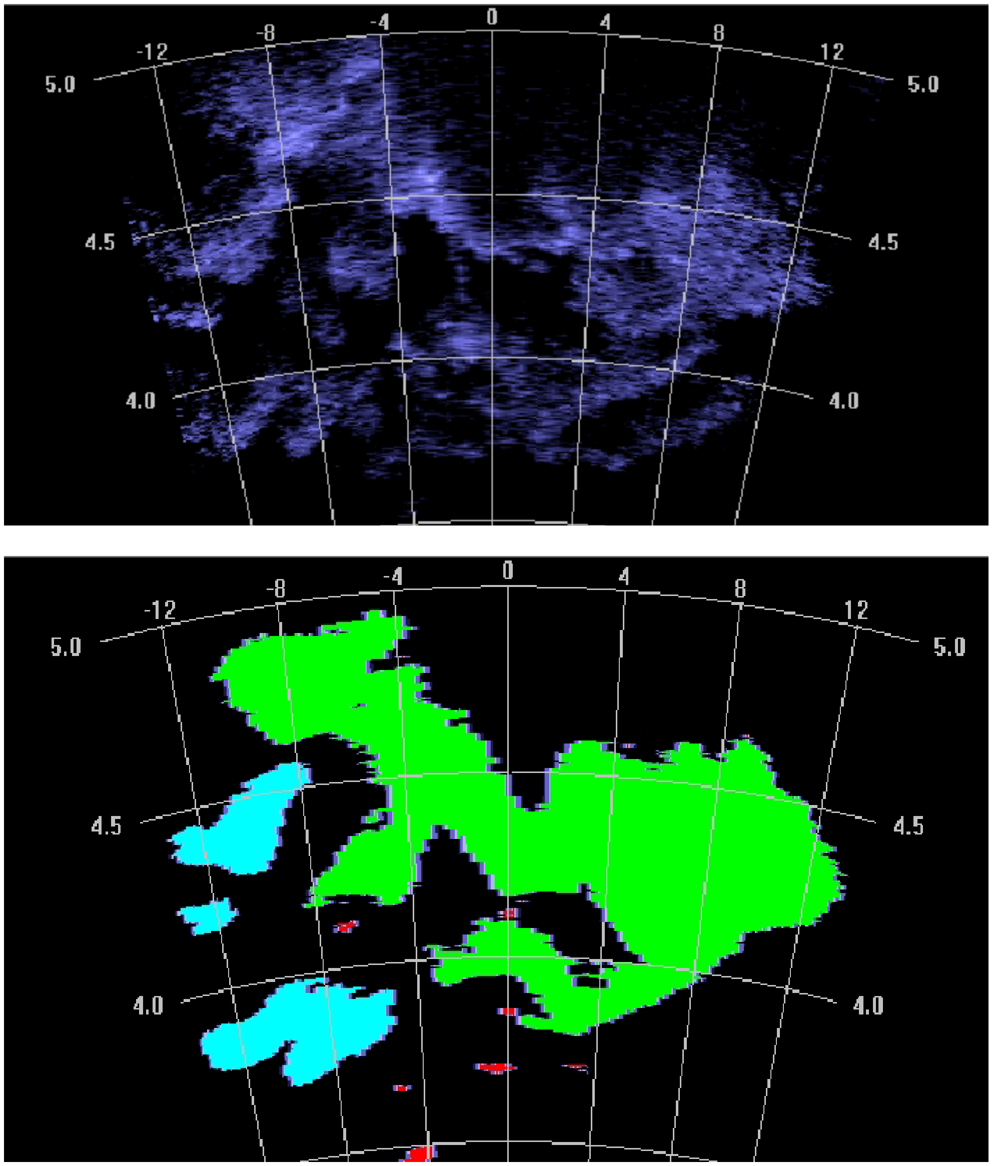

Fig. 6: Upper image shows an example acoustic cross section of plume, lower image shows plume area calculation using motion tracking with a 6dB threshold.

Oil Composition

To determine the gas/oil ratio flowing out of the well, we employed an isobaric gas-tight sampler (IGT; Fig 7) This device was designed for collecting hydrothermal vent fluids and hydrocarbon gases at temperatures up to 400 ºC and capable of preserving the integrity of samples for months until lab-based analysis. More traditional oceanographic water sampling equipment would not be able to prevent degassing during ascent to the ocean surface.

On June 20, 2010, some time after placement of tophat #4 on the riser stub, we collected a sample with a remotely operated vehicle deployed from the *Ocean Intervention III* (Fig 8). Briefly, the snorkel on the sampler was inserted immediately above the riser pipe into the flow of oil and gas. The thermistor attached next to the tip of the snorkel read a temperature of 100 ºC during sampling (with an ambient temperature of 4.4 ºC).

Once the sampler was removed from the ROV on the deck of the *Ocean Intervention III*, its pressure was measured at >2000 psi, consistent with the pressure of the water depth of collection. Following strict chain-of-custody procedures, the sampler was returned to Woods Hole, MA and secured.

The contents of the IGT were then determined by depressurizing the sampler into a custom-built system for collecting the oil and gas (Fig 9). The internal pressure of the sampler measured at WHOI prior to analysis was the same as when measured weeks earlier, indicating no leaks. By measuring the total volumes of oil and gas recovered, a gas/oil ratio of 309 at room temperature and atmospheric pressure was determined. For in-situ calculations, the measured laboratory gas volume was translated to a theoretical volume at 150atm and 4.4 °C. At this temperature and pressure propane and higher chained hydrocarbons were estimated to be in the form of a liquefied condensate and only methane and ethane were assumed to be in gas form at each of the leak sites. Gas analysis of the sample indicated that methane and ethane represent approximately 85.4% of the gas. Thus, the oil fraction at ambient seafloor pressure (150 atm) and temperature (4.4 °C) is 43.7% of the bulk flow.

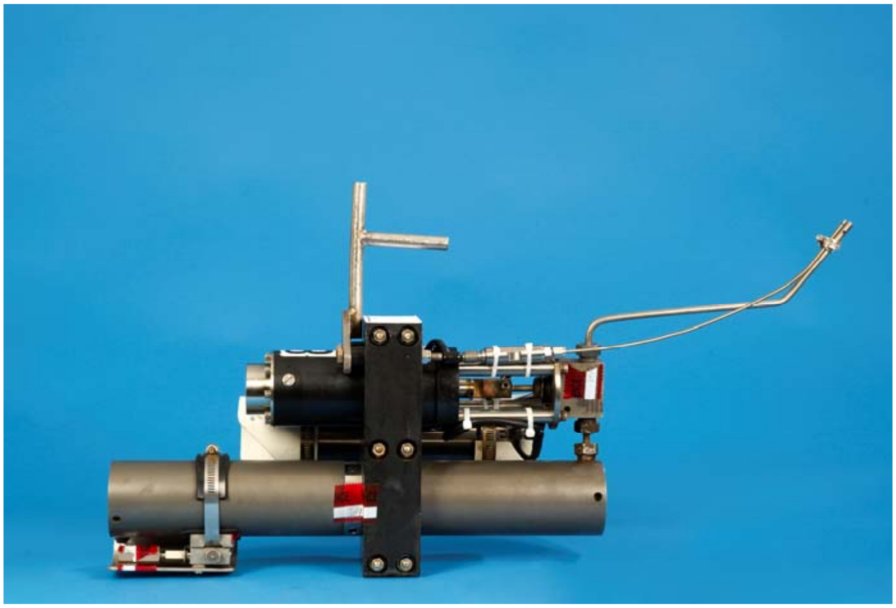

Fig 7: Image of the isobaric gastight (IGT) sampler. The snorkel and thermistor are in the upper right-hand side of the device.

Fig. 8: Image of the IGT sampler prior to integration onto the Millennium 42 ROV on June 20-21, 2010.

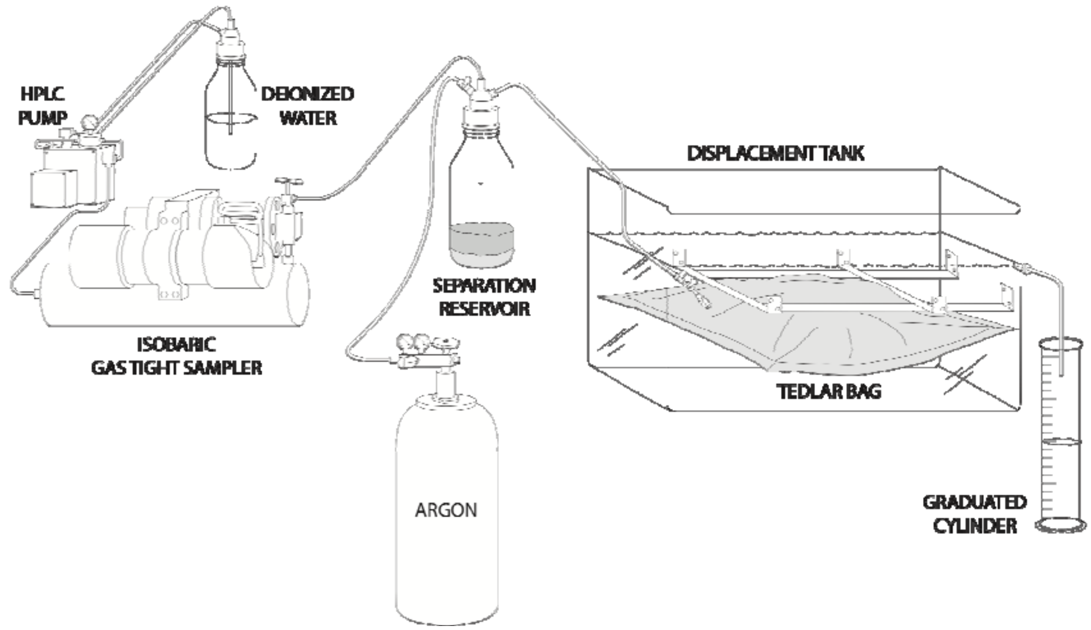

Fig 9: Schematic of system used to depressurize the IGT in the laboratory in Woods Hole to determine the gas/oil ratio from the sample collected within top hat #4.

Oil flow rate model

Based on empirical data for a wide range of free round jets emanating into a quiescent fluid, in the region where the jet is fully developed, velocity profiles obey laws of similarity such that the fluid velocity profile for a cross section of the jet maps identically to those at increasing distances from the source, once jet growth is accounted for. The distance x_c beyond which the jet velocity profiles become self-similar can change with the velocity profile at the orifice, depending on the boundary layer development inside the pipe leading up to opening. Well beyond x_c the initial jet velocity profile at the orifice becomes inconsequential.

To estimate the flow from the riser leak data obtained using an acoustic Doppler current profiler (ADCP) was combined with cross-sectional area measurements obtained using the imaging sonar system mounted to the Maxx3 ROV. The measured water depths of the riser leak source and BOP kink leak source were estimated to be 1513.9 meters and 1503.5 meters, respectively and using ROV data. The imaging sonar cross sections were measured at 1510.3 meters for the riser jet and 1502.2 meters for the BOP jet.

The four beams of the ADCP were arranged with beam 4 horizontal and co-planar with the Imaging sonar and Beam 3 pointing upwards at 60 degrees. Fig. 10 shows a schematic of the measurement setup. Data was binned to obtain velocities within the jet. The jet was defined based on the equivalent radius of the plume cross section and augmented by an expansion coefficient 0.11 times the distance traveled. Figs 11 and 12 show the velocity measurements defined as being within the plume radius. Each of these velocity values within the plume radius were then back-projected downward to the imaging sonar plane using the equation

$$u_1 = u_2 \, (1 + \Delta x / x_1)$$

where u_1 is the calculated velocity at the sonar imaging plane, u_2 is the measured velocity at a height of Δx above the imaging sonar plane, and x_1 is the sonar imaging plane's height above the source.

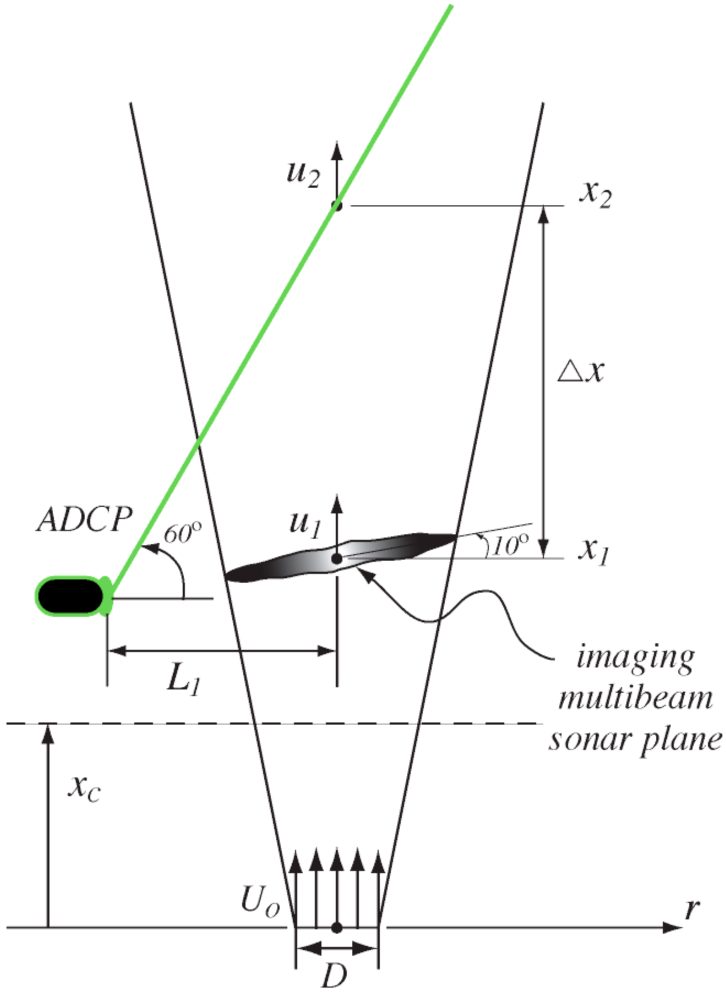

Fig 10: Diagram of computational model used to calculate flow rate using measured cross sectional area estimates and velocity measurements.

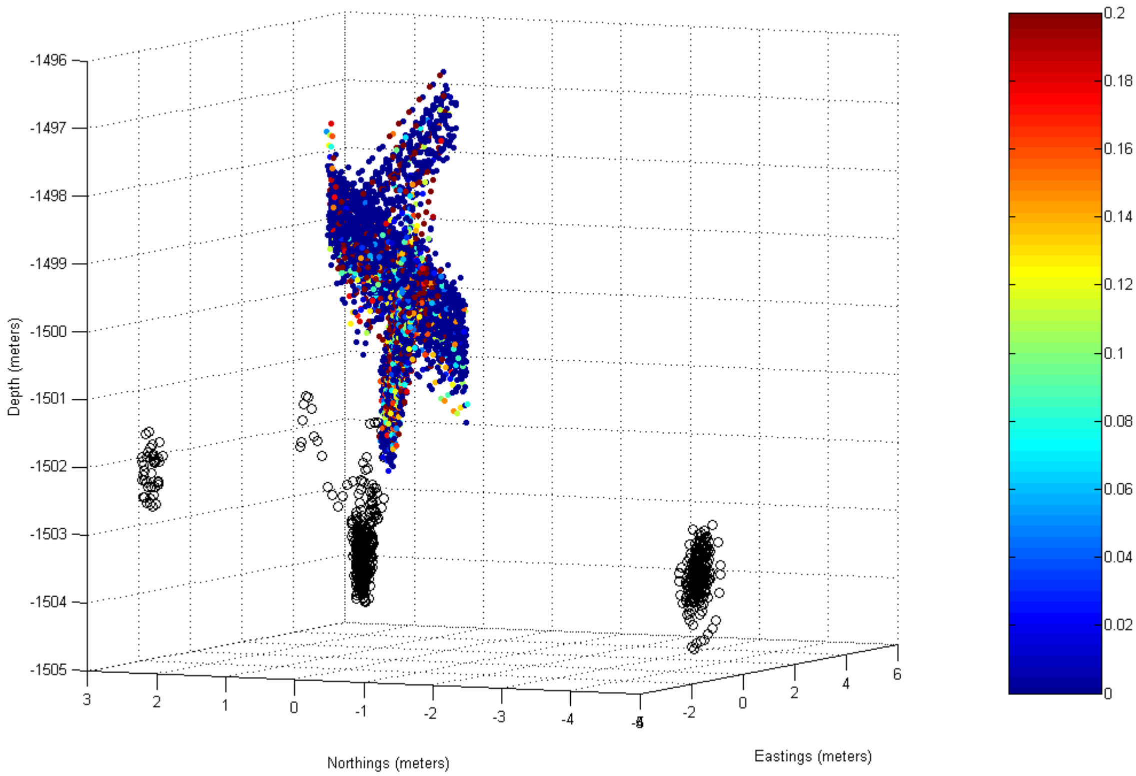

Fig 11: 3D reconstruction of the plume velocity field measured above the BOP kink, only including points defined as being within the plume radius. Colors indicate velocity in meters per second. The black circles indicate ROV positions.

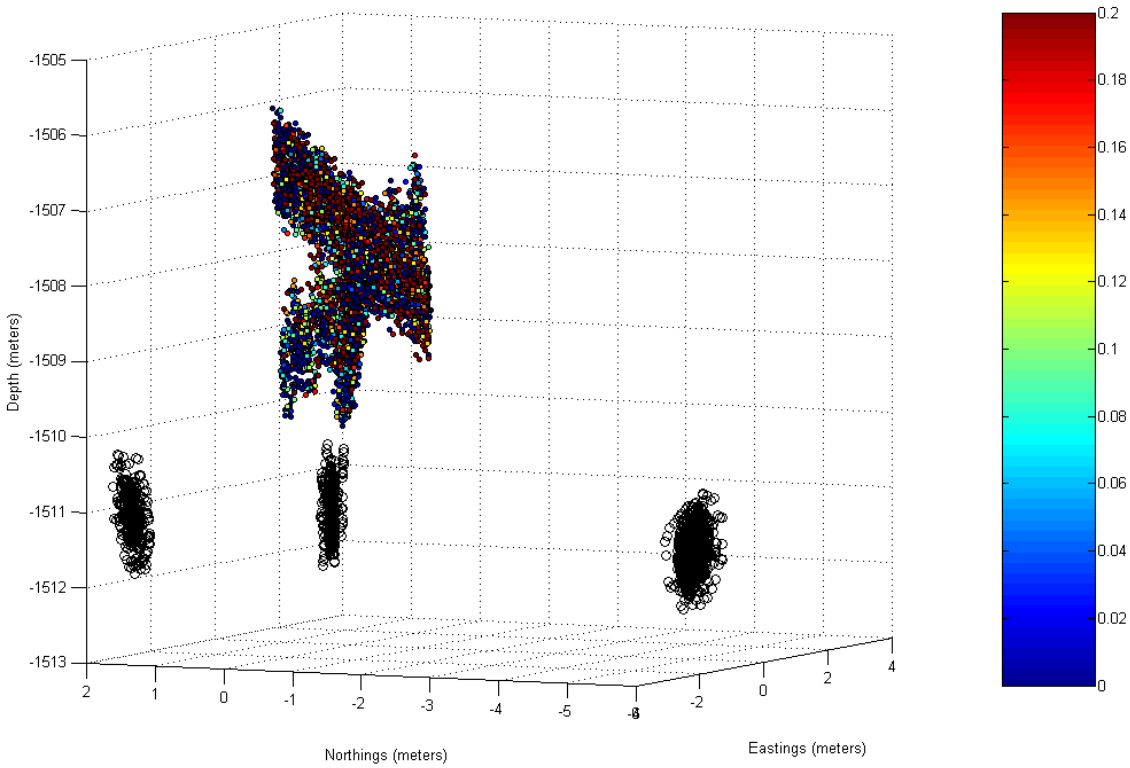

Fig 12. 3D reconstruction of the plume velocity field measured above the riser section, only including points defined as being within the plume radius. Colors indicate velocity in meters per second. The black circles indicate ROV positions.

To calculate the (total) bulk volume flow rate the average cross sectional area (S_1) measured by imaging sonar is multiplied by the average u_1 vertical velocity at the sonar plane. This bulk flow was then multiplied by the oil fraction (previously defined as 0.437) to yield an oil flow rate in m/s. This method yields a volumetric oil flow rate on 5/31/2010 of 0.0781 m^3/s from the leak at the BOP kink, and 0.171m^3/s from the leak at the end of the broken riser. This converts to a rate of 40,700 bbl oil/day from the end of the broken riser and 18,500 bbl oil/day from the BOP kink, or a total flow rate of 59,200 bbl oil/day on 5/31/2010.

Based on this 5/31/10 flow estimate and the DOE Tri-Lab Flow Modeling Team's WIT shut-in estimate (53,000 bbls/day), a linear flow rate trend is extrapolated for the interval between 4/20/10 and 7/14/10. The summation of each day's flow rate is then used to calculate a cumulative total flow from the well. This approach is consistent with the hypothesis that flow rate decreases approximately linearly with time as a result of well pressure decrease. Using this linear fit, a cumulative release of approximately 5 million barrels is estimated to have leaked from the well. Net leak to the ocean can be calculated as the cumulative release minus the oil collected by BP using the RITT, tophat, and BOP lines, or approximately 4.2 million barrels (Fig 13).

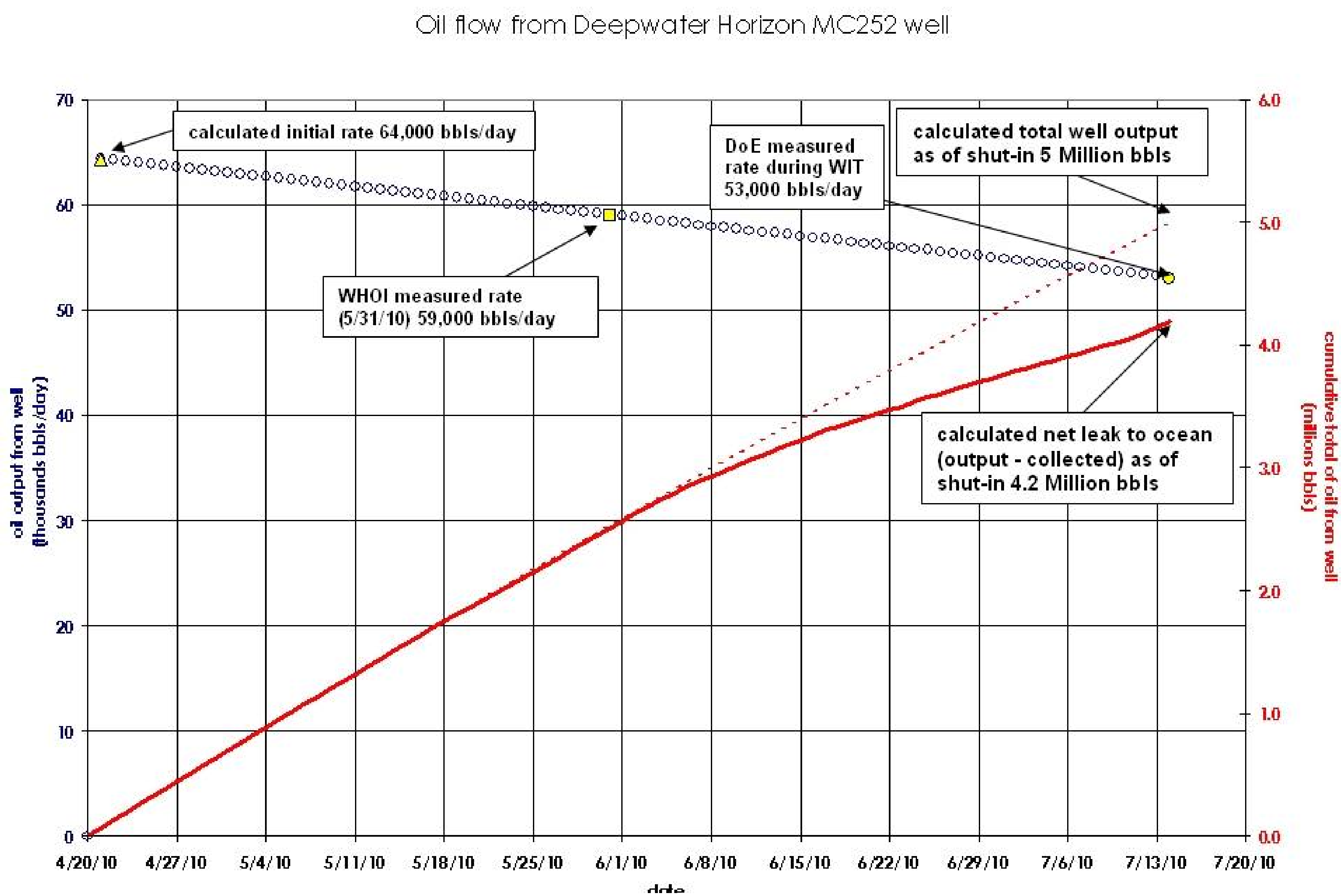

Fig 13: flow estimates of the Deepwater Horizon well