Appendix D – Plume Calculation Team 2010; Particle Image Velocimetry Report

Plume Calculation Team. 2010. Deepwater Horizon Release, Estimate of Rate by PIV. Plume Team report to the Flow Rate Technical Group. July 21, 2010.

Note: Due to the length of the full Plume Calculation Team report, this appendix includes only the summary section. The full report can be downloaded at: http://www.usgs.gov/oilspill/ and http://www.doi.gov/deepwaterhorizon/index.cfm

Deepwater Horizon Release Estimate of Rate by PIV

July 21, 2010

Plume Team - FRTG

Report to

Dr. Marcia Mcnutt, USGS Director and Science Advisor to the Secretary of the Interior
Lead to the National Incident Command Flow Rate Technical Group

Prepared by

Plume Calculation Team

Aliseda, Alberto	Assistant Professor of Mechanical Engineering, University of Washington
Bommer, Paul	Senior Lecturer, Petroleum and Geosystems Engineering, University of Texas at Austin
Espina, Pedro	National Institute of Standards and Technology
Flores, Oscar	Department of Mechanical Engineering at University of Washington
Lasheras, Juan C.	Penner Distinguished Professor of Engineering and Applied Sciences, University of California at San Diego
Lehr , Bill (Lead)	Senior Scientist, National Oceanic and Atmospheric Administration Office of Response and Restoration
Leifer, Ira	Associate Researcher, Marine Science Institute and Institute for Crustal Studies, University of California, Santa Barbara
Possolo, Antonio	National Institute of Standards and Technology
Riley, James	PACCAR Professor of Mechanical Engineering, University of Washington
Savas, Omer	Professor of Mechanical Engineering, University of California at Berkeley
Shaffer, Franklin	Department of Energy National Energy Technology Laboratory
Wereley, Steve	Professor of Mechanical Engineering, Purdue University
Yapa, Poojitha	Professor of Civil and Environmental Engineering, Clarkson University

All the calculations and conclusions is this report are preliminary, and intended for the purpose, and only for the purpose, of aiding the response team in assessing the extent of the spilled oil for ongoing response efforts. Other applications of this report are not authorized and are not considered valid. Because of time constraints and limitations of data available to the experts, many of their estimates are only approximate, subject to revision, and certainly should not be used as the federal government's final values for assessing volume of the spill or its impact to the environment or to coastal communities. Each expert that contributed to this report reserves the right to alter his conclusions based upon further analysis or additional information. Note that this version of the report was modified post-July 21, 2010 to correct a typographic error on page 3 and clarify a point about the DOE team data on page 16.

Table of Contents

Executive Summary

The plume modeling team observed video both before and after the cutting of the riser pipe. The 'before' video looked at the end of the original riser leak and from the kink in the riser and from the kink leak above the Blowout Preventer (BOP). The later video examined the leakage shortly after the severing operation but before any capping operation.

The main method employed to make estimates was a common fluid dynamic technique called particle image velocimetry (PIV). While difficult in practice, it is simple in principle. A flow event, e.g., an eddy or other identifiable item, is observed at two consecutive video frames. Distance moved per time between frames gives a velocity, after adjustment for viewing angle and other factors. Repeated measurement over time and space give an estimated mean flow. Flow multiplied by cross-section area of the plume gives a volume flux.

Because of time and other constraints, only a small segment of the leakage time was examined, and assumptions were made that may through later information or analysis be shown to be invalid. For example, the Team assumes that the average flow between the start of the incident and the insertion of the Riser Insert Tube Tool (RITT) was relatively constant and the time frames that were included in the examined videos were representative of that average. If this were not true, then the actual spillage may differ significantly from the values stated below.

Most of the experts, using the limited data available and with a small amount of time to process that data, concluded that the best estimate for the average flow rate for the leakage prior to the insertion of the RITT was between 25 to 30 thousand bbl/day. However, it is possible that the spillage could have been as little as 20,000 bbl/day or as large 40,000 bbl/day. Further analysis of the existing data and of other videos not yet viewed may allow a refinement of these numbers.

The video of the post-cut was of higher quality than earlier video. The best estimate of the PIV experts was for a flow of 35,000 to 45,000 bbl with the possibility that the leak could be as large as 50,000 bbl/day. After consultation with groups from the Department of Energy that were using pressure readings from inside the Top Hat to estimate flow, a joint estimated range of 35,000 to 60,000 bbl was provided to the National Incident Command (NIC).

Deepwater Horizon, on fire after the explosion

Background

When the Deepwater Horizon drilling unit sank in the Gulf of Mexico, initial loss estimates were given as 1000 bbl/day. By April 26, it was obvious that this estimate was too low. Based upon visual observations of oil on the surface, a working number of 5000 bbl/day was adopted. However, the large amount of surface oil, the volume recovered or burned, and a re-examination of the pipe leakage, convinced the National Incident Command (NIC) that it was necessary to revisit the 5000 bbl/day number.

On May 19, the NIC Interagency Solutions Group established the Flow Rate Technical Group that has as one of its subgroups the Plume Team represented in this report. Experts on fluid dynamics, subsurface well blowouts, petroleum engineering and oil spill behavior were assembled as part of a larger effort to improve spill size estimation. The team consists of both government scientists and leading scholars at academic institutions throughout the United States.

On May 27, the Team issued an Interim Report that established an estimated range for the minimum possible spillage rate but did not issue an estimate for a possible maximum value because the quality and length of the video data could not support a reliable calculation. Instead, they requested, and received, more extensive videos from British Petroleum (BP). See Table 1.

Table 1: List of Video Segments on BP-Provided Hard-Drive

subsea 7 — DVR REGISTER

Project Title	Deepwater Horizon	Project No.	TC1024
Archive Name	BP_Deepwater_Horizon	Client	BP
Vessel	Skandi Neptune		
Transmittal	TC1024/BPDW/TRANS/007	To	S. Dietz 24/05/2010
Seagate 500Gb Drive Contents			

Directory Name	Start KP	End KP	Dive	Date	Time Start	Time End	Remarks
On First RAID Drive, Retrieved from LTO4 tapes 4 and 5							
A.Plume_Monitoring	NA	NA	H14/005	11/05/2010	07:22	08:22	Large Plume Monitoring, Measurment Ops
A.Plume_Monitoring	NA	NA	H14/005	12/05/2010	08:03	08:33	Large Plume Monitoring
A.Plume_Monitoring	NA	NA	H14/006	12/05/2010	10:04	11:04	Large Plume Monitoring
Retrieved from Second RAID Drive (In use on Skandi Neptune as of 24/05/10)							
A.Plume_Monitoring	NA	NA	H14/006	13/05/2010	15:08	18:50	Large Plume Monitoring
A.Plume_Monitoring	NA	NA	H14/006	13-14/05/2010	20:38	06:28	Large Plume Monitoring
D.Chemical_Dispersing_Ops	NA	NA	H14/008	14/05/2010	15:27	16:30	Dispersion at Large Plume
D.Chemical_Dispersing_Ops	NA	NA	H6/030	14/05/2010	15:54	16:17	Dispersion at Large Plume
J.Plume_Test_with_OI3	NA	NA	H14/006	14/05/2010	16:30	20:25	Plume testing with OI3
A.Plume_Monitoring	NA	NA	H14/006	14-15/05/2010	20:25	01:03	Plume Monitoring
I.Dredging_Ops	NA	NA	H6/032	15/05/2010	01:22	02:52	Dredging Ops
D.Chemical_Dispersing_Ops	NA	NA	H6/032	15/05/2010	02:52	03:42	Dispersion at Large Plume
D.Chemical_Dispersing_Ops	NA	NA	H14/007	15/05/2010	03:45	14:38	Dispersion at Large Plume
I.Dredging_Ops	NA	NA	H6/032	15/05/2010	03:53	06:25	Dredging Ops
I.Dredging_Ops	NA	NA	H6/034	15/05/2010	06:32	10:11	Dredging Ops
I.Dredging_Ops	NA	NA	H6/035	15/05/2010	12:45	14:31	Dredging Ops
H.Special Task\C.Hose Installation	NA	NA	H14/007	15/05/2010	14:38	18:50	Second 600' hose installation
A.Plume_Monitoring	NA	NA	H14/007	15-16/05/2010	18:50	01:15	BOP Monitoring (First 1/2 hour is debris)
K.Debris_Inspection	NA	NA	H5/035	15/05/2010	18:58	19:31	Debris Inspection
A.Plume_Monitoring	NA	NA	H5/035	15-16/05/2010	22:58	01:15	BOP Monitoring

After May 16, the Riser Insert Tube Tool (RITT) was placed into the riser at the main leak point, reducing the oil being released into the environment from this source. The recovery rate of gas and oil for the tube between the insertion and May 25 is shown below.

Table 2: Gas and Oil Flow Rates from the Riser Insert Tube Tool

Date	Oil (bo)	Gas (mmcf)	Oil + Gas (boe)	Gas Portion (%)	High Oil (bopd)	Low Oil (bopd)	High Gas (mmcf/d)	Low Gas (mmcf/d)
16-May-2010	290	0.9	440	34%				
17-May-2010	1,410	3.5	2,015	30%				
18-May-2010	1,930	10.4	3,721	48%	2,191	1,066	12.5	5.3
19-May-2010	3,014	17.5	6,025	50%	4,102	1,521	23.2	10.5
20-May-2010	2,185	15.6	4,882	55%	5,389	44	32.4	4.4
21-May-2010	2,173	4.9	3,025	28%	3,599	646	7.6	1.8
22-May-2010	1,361	7.1	2,586	47%	4,531	0	14.7	2.0
23-May-2010	1,120	2.9	1,616	31%	3,103	0	5.6	2.0
24-May-2010	6,078	9.8	7,771	22%	8,961	2,523	16.1	2.0
25-May-2010	2,596	15.8	5,316	51%	7,337	877	30.4	9.4
Total	22,158	88.4	37,397	41%	8,961	0	32.4	1.8
Average	2,430	9.7	4,106	40%				

As can be seen from Table 2, the amount of oil and gas fluctuated significantly. Part of this fluctuation was due to movement of the end of the RITT in the riser due to tidal effects and the natural separation of the oil from the gas in the riser (gas tends to rise to the top). However, examination of the videos also shows significant intermittency in the gas fraction of the flow.

During the time period of the videos examined by the Team, there were two main leak points, shown in Figure 1. The figure also displays the ultimate fate of the released fluid and gas. The main leak, until the most recent severing operation, came from the broken end of the riser, some distance away from the Blowout Preventer (BOP). The leakage was only from the annulus (inside pipe diameter of nineteen and a half inches) surrounding an interior drill pipe (pipe diameter of six and five eighth inches). According to BP, the mouth of the riser was damaged in the initial incident, reducing the cross-sectional area by 30%. Figure 2 shows the damaged riser. After May 1, and perhaps earlier, a second leak source appeared in the kinked riser above the BOP. The number of holes and leakage volume in the kink has increased over time, as BP has attempted to stop oil release by such operations as the RITT and Top Kill.

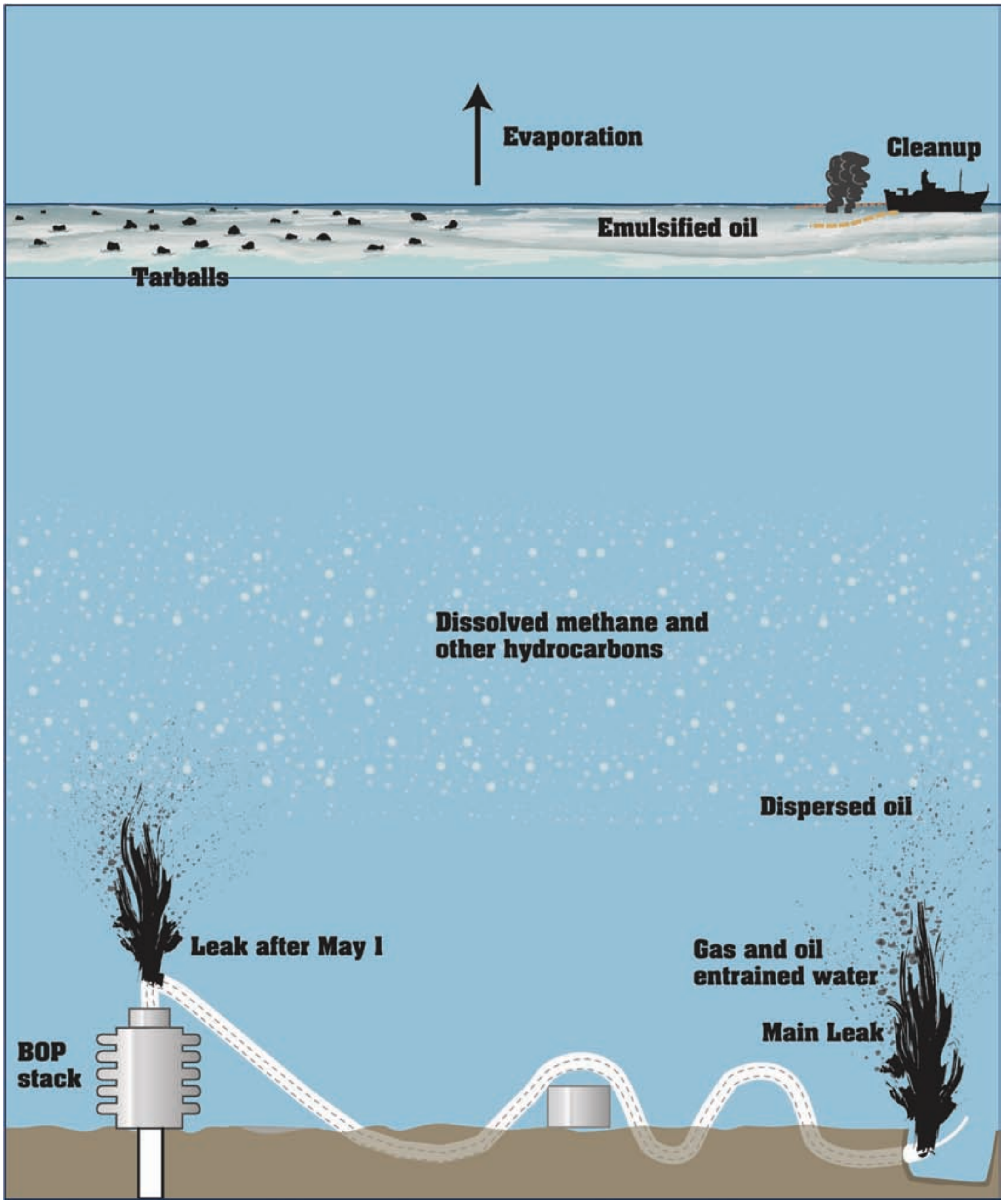

Figure 1: Graphic Showing Leaks and Oil Fate

At certain times, a dispersant wand was inserted in the plume and dispersant added. These chemicals are designed to lower surface tension and reduce the average oil droplet size. Unfortunately for flow rate estimation, they add an additional component to the flow and produce a less defined plume. Measurements were not done using video while dispersant was being applied

While particle image velocimetry (PIV), described in the next section, was the main approach to estimating the leak rate, alternative approaches were used to provide an additional credibility check on the results from the PIV method. These included looking at expected flow based upon properties of the reservoir and reservoir fluid, comparison of this release with a controlled experiment in the North Sea, using well-established similarity characteristics of turbulent jets, and calculating a possible release size, based upon surface oil and oil recovered or burned. Appendix 2 describes an estimate made using one of these alternative methods. Some of these same methods will be or are being examined by other Flow Rate Technical Group teams.

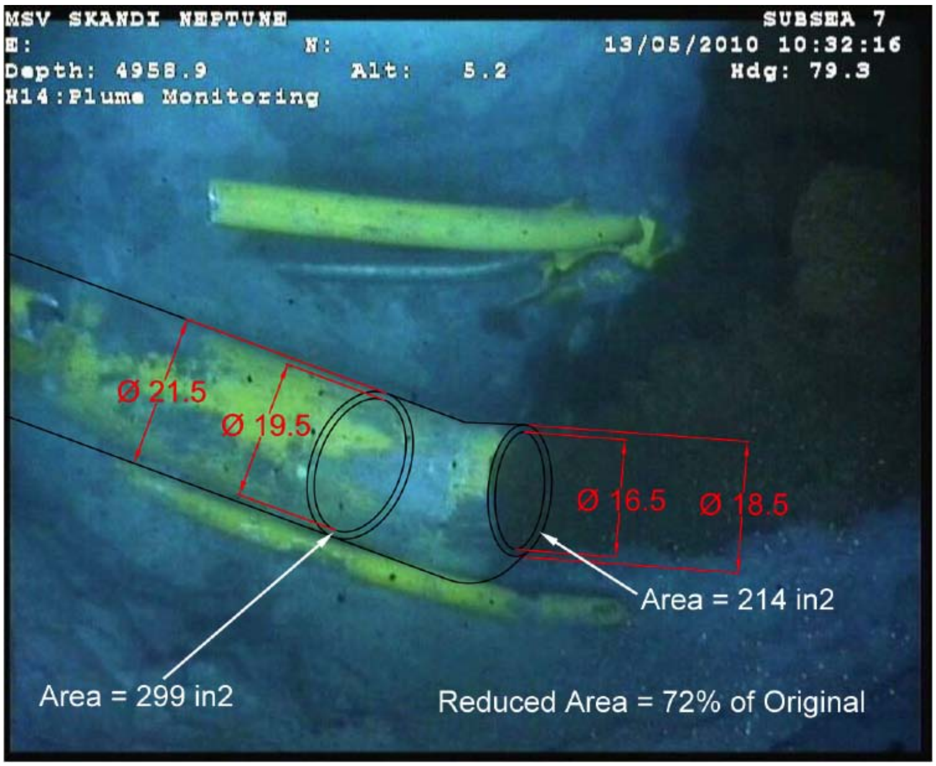

Figure 2: Riser Outlet Showing Its Reduced Cross-Sectional Area

Particle Image Velocimetry

The term particle image velocimetry was first proposed in 1984 by R. J. Adrian, a reviewer of this report. While difficult in practice, PIV is simple in principle. In this method a flow event, e.g., an eddy or other identifiable item, is observed at two consecutive video frames. Distance moved per time between frames gives a velocity, after adjustment for viewing angle and other factors. Repeated measurement over time and space give an estimated mean flow. Flow multiplied by cross-section area of the plume gives a volume flux.

Many researchers were drawn to PIV because it provided a new way to study turbulent flow structure. Turbulence is a phenomenon that is characterized by multiple length scales. To measure turbulent flow, therefore, the method must be able to operate at different scales with possible flow movement in all directions. True PIV uses small, solid particles illuminated by laser light and recorded under very short time exposures. In this instance, natural markers in the flow were employed. These markers themselves changed over time, increasing the complexity of the problem.

Figure 3 illustrates the approach. Because the flow velocity is not uniform throughout the plume, multiple locations, known as interrogation spots, must be sampled to estimate and average velocity. Similarly, the cross-sectional area is time and spatially dependent as well as having diffuse boundaries so that an average cross-section, dependent upon the location of the interrogation spots, needs to be calculated. A further challenge for measuring the flow in this case is that it is not spatially or temporally uniform in mixture of gas and fluid.

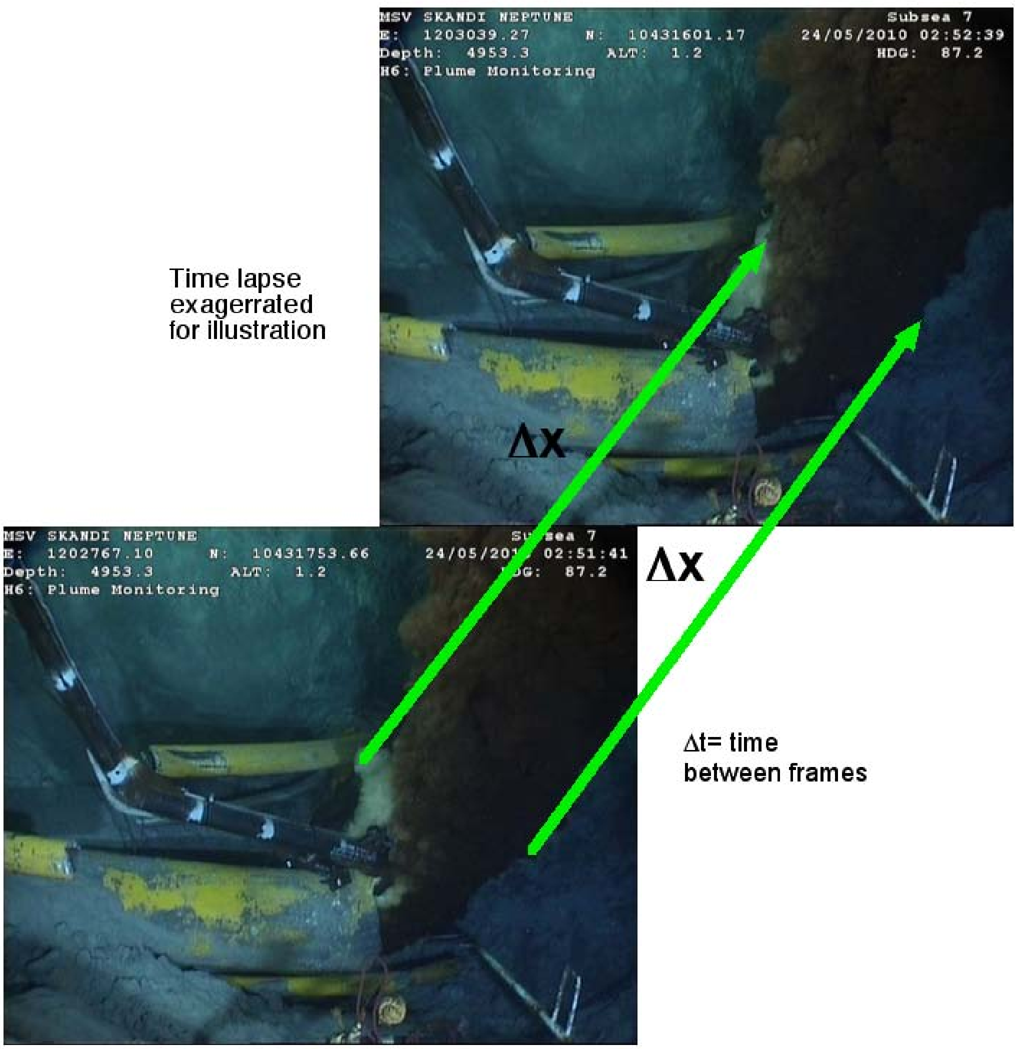

Figure 3: Illustration of Particle Image Velocimetry

For each of the interrogation sites a vector velocity $\Delta X/\Delta t$ is computed. The vector average of these velocities provides an average velocity. Combined with an average cross-section area, this yields a net flux of both gas and oil. A key parameter was this average ratio of gas to liquid. This term seemed to vary over the time period of the spill and during the time of the video clips. Increasing gas increased the velocity of the plume but decreased the mass flow. Analysis of the available short movies of the riser flow shows the existence of periods when the flow oscillates from pure gas to seemingly pure oil. This could be an indication of Slug Flow Regime. These periods of gas-oil flow fluctuation are in the range of minutes. Longer periods may also exist but would require examination of longer clips to determine.

Another key question was the fluid velocity at the interior of the jet, something that obviously could not be directly observed. The different PIV experts approached this problem in different ways. Most assumed a correction factor for the interior velocity, usually two or two multiplied by the square root of two. One expert chose larger scale structure that he believed would feel the interior flow directly so that no correction was necessary.

Kink Leak

The Kink leak began sometime around May 1. The Team has requested clarification of the exact date from BP. The number of holes in the riser pipe at the kink increased on or before May 15. The team believes that the amount of escaping oil from this source increased as the holes widened, increased in number, and as the RITT insertion placed more upstream pressure on the riser. Estimation of the flow from the kink was challenging because only one plume, labeled J1 below, was clearly visible and unobstructed in the video.

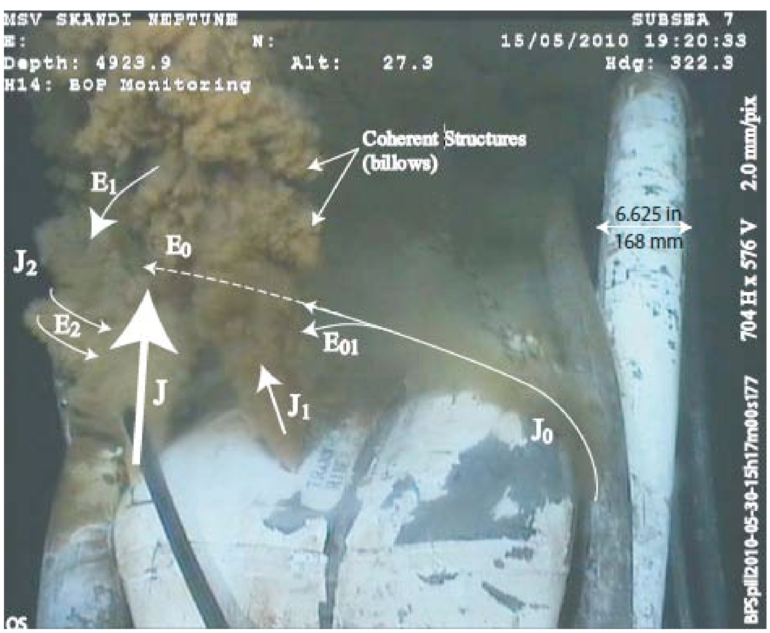

Figure 4: Kink Leak (Annotations by Savas)

New Leak at Severed Riser

By June 3, BP had severed the riser just above the BOP. According to the oil company estimates, this was expected to increase the total leak rate by approximately 20%. Surprisingly, the interior of the riser pipe contained not one, but two pieces of drill pipe inside (Figure 5). One team member speculated that the drill pipe snapped during the accident into several segments that would fit side by side inside the riser. The team requested from BP videos of the leak after the cut but before the installation of a dome designed to capture part of the flow. The damage to the riser during cutting complicated the task of estimating flow cross section.

Figure 5: Cut Riser Showing Two Pipes Inside

The quality of the video was much better for the severed riser flow than the video used for earlier estimates. This allowed for greater confidence in calculated flow. The PIV experts were able to use the visible flange and bolts as references although parallax adjustments were required. There was a noticeable difference in the color of the two distinct plumes emanating from the cut riser. BP attributed this to greater gas content in the lighter plume.

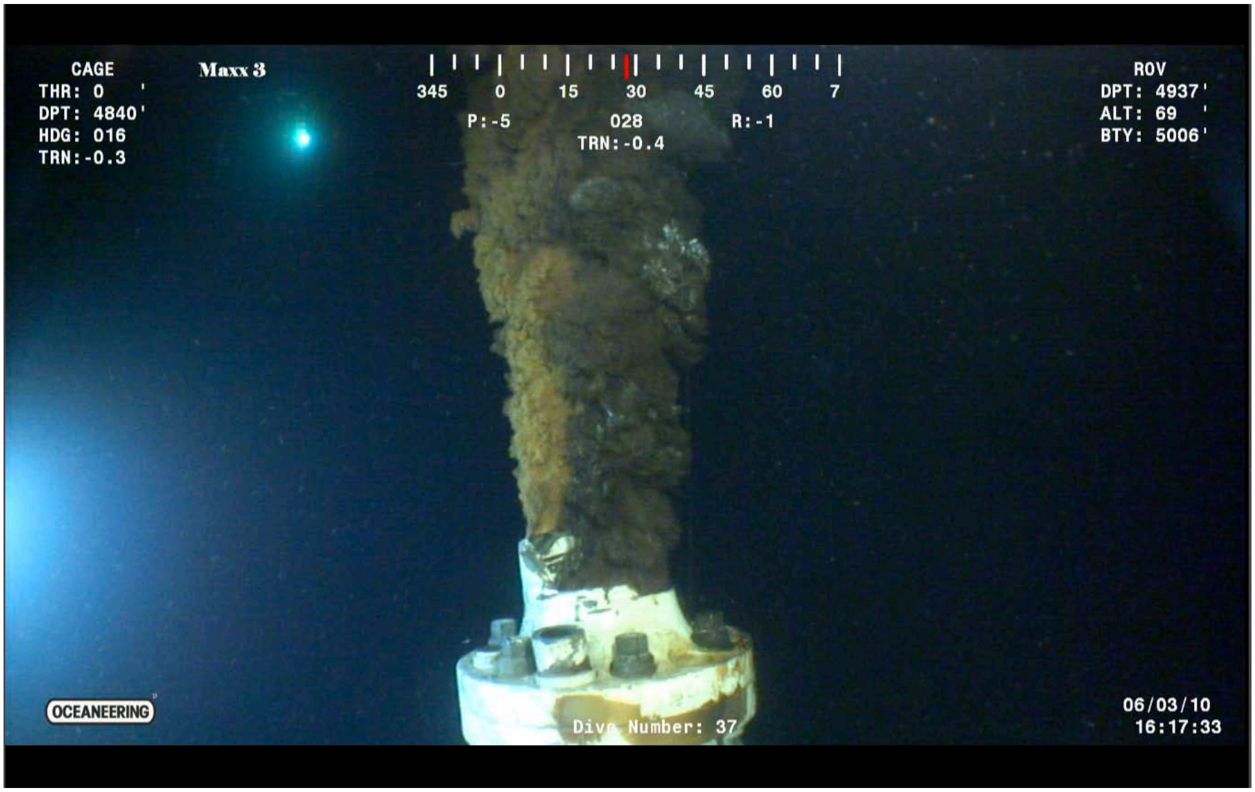

Figure 6: Cut Riser Leak

Shortly after the cut, BP placed a 'Tophat' over the riser stub, allowing the capture of some of the oil. This Tophat had vents that could be equipped with a pressure gauge, allowing an alternative method to estimate the flow. Teams affiliated with the Department of Energy, using the subsequent pressure readings to estimate flow, pooled their findings with the Plume Team results to produce a common estimate for operation purposes to the National Incident Command.

Conclusions

As with earlier estimates, the conclusions in this report are only to aid the Response, not to determine the final Federal estimate of spillage. Because of time and other constraints, only a small segment of the leakage time was examined, and assumptions were made that may through later information or analysis be shown to be invalid. For example, the Team assumes that the average flow between the start of the incident and the insertion of the RITT was relatively constant and the time frames that were included in the examined videos were representative of that average. If this were not true, then the actual spillage may differ significantly from the values stated below.

Most of the experts have concluded that, given the limited data available and the small amount of time to process that data, the best estimate for the average flow rate for the leakage prior to the insertion of the RITT is between 25 to 30 thousand bbl/day. However, it is possible that the spillage could have been as little as 20,000 bbl/day or as large 40,000 bbl/day. Further analysis of the existing data and of other videos not yet viewed may allow a refinement of these numbers.

For the time period after the riser cut, most of the experts concluded that the likely range for the flow was between 35,000 and 45,000 bbl/day but could be as high as 50,000 bbl/day.

The Plume Team then met with other experts from the Department of Energy, who employed non-PIV methods to estimate flow rate. The combined groups reached a consensus estimated flow range of 35,000 bbl/day to 60,000 bbl/day.