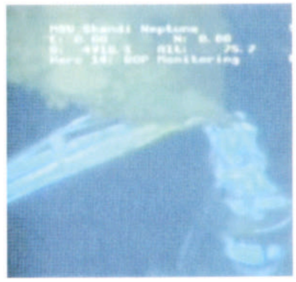


Estimated Leak Rates and Lost Oil from the Deepwater Horizon Spill, May 27, 2010

Interim Report to the Flow Rate Technical Group

Plume Calculation Team

Lead

Bill Lehr	NOAA Office of Response and Restoration

Team

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

PURPOSE

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.

To meet the emergency nature of this incident, the conclusions in this report are being provided to the NIC without external peer review. The team is continuing its work to refine its estimates.

CONCLUSIONS

The total leakage and gas/oil mixture from the two sources of the spill, the broken riser and the kink above the BOP, appears to vary significantly over time. Part of this variation may be an artifact of the ROV operations themselves. An accurate estimate would require longer and better quality videos of the leak points, particularly the main leak in the riser pipe. Based upon the incomplete and often poor quality data available to the experts, only a range of values that represent an estimated minimum can be given. Using estimates from the video and auxiliary data given them by BP, the consensus of most of the experts is that the leakage at the time of the viewed video clips averaged at least 12, 000 to 25,000 bbl of oil per day plus considerable natural gas, and could possibly be significantly larger if the conservative assumptions used to make the estimate were relaxed. If this leak rate range represents the average spill rate for the entire incident, then this spill is larger than any other spill in U. S. exclusive economic zone waters.

HISTORY

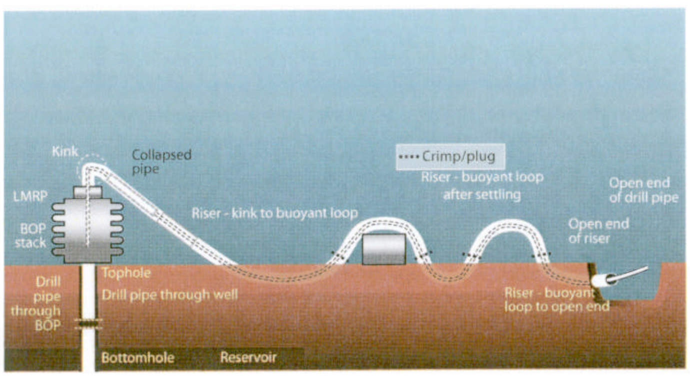
On Thursday, April 22, the Deepwater Horizon drilling unit sank in the Gulf of Mexico. Initial loss estimates were given as 1000 bbl/day. By April 26, it was obvious that this estimate was too low. Based upon visual observations of oil on the surface and a discussion with BP on the leaking pipe, a working 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 response that it was necessary to re-visit the 5000 bbl/day number.

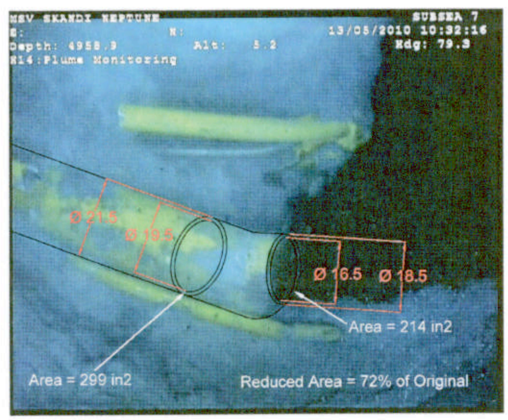
On May 19, the NIC Interagency Solutions Group established the Flow Rate Technical Group that has as one of its subgroups the plume team represented in this report. Experts on fluid dynamics, subsurface well blowouts, petroleum engineering and oil spill behavior were assembled as part of a larger effort to improve spill size estimation.

According to information provided by BP representatives, there are currently two leaks. One is from the end of the riser, now with the insertion of the RITT, and a second leak where the riser bends away from the BOP. The exiting liquid density is 44.4 lbs/ cu. ft and the exiting gas at that depth is 12.3 lbs/cu.f t. The diameter (inside) of the riser is 19.5 inches. It was partially obstructed by the interior drill pipe of $6\frac{5}{8}$ inch diameter that is now blocked. The mouth of the riser is bent, reducing the opening to 70% of its original area.

BP provided to the group of experts certain materials and four sets of videos. The experts decided that the first two video set were of insufficient length and quality to make reliable calculations. Both sets of videos appeared to be videos of videos, rather than original high definition images necessary to make an accurate estimate.

Reservoir/Riser/Well System





More recently, BP has provide the team with better quality video, much of which is still being processed

DESCRIPTION OF APPROACH

The plume modeling team observed video from both the end of the riser where the majority of the flow is escaping and from the kink in the riser where a smaller amount exits through small slits in the top of the riser. The main method employed to make their estimates was through a common fluid dynamic technique called particle image velocimetry (PIV). While difficult in practice, it 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. Some of the experts expressed the opinion that while the technique is intended for flow fields that are carefully seeded with tracers, in its application here it relies on the natural contaminants as well as the flow features marked by the mixing of the jet with the sea water. These experts concluded that the application of PIV in some ways mimics Image Correlation velocity (ICV) which attempts to fit 'a best' velocity field to minimize some cost function and in this application is likely to

provide (1) a depth-averaged entrainment velocity and (2) a phase speed of the features at the edge of the jet.

The challenges this team faced in getting reliable results were many. First, they only had a limited window of data in time to choose from. They had to select data from before the RITT was inserted into the riser as that tool captured a variable amount of flow. They needed a time window when application of subsea dispersant was not perturbing the flow. They required footage from after the period when a trench was excavated at the end of the riser to better expose the end of the plume. Most challenging was getting good lighting and unobstructed views of the plumes from work-class ROV's not intended to capture research-quality footage and occupied doing other tasks at the time.

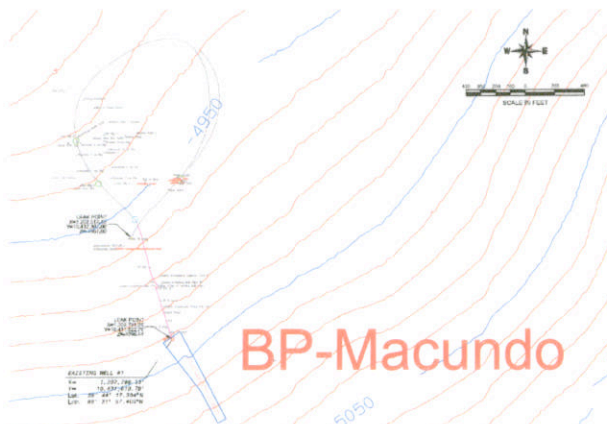
Second, perfecting the methodology for calculating multiphase flow (oil, water, gas, hydrate in poorly known ratios) under very high pressure is worthy of a research effort. This is not a turn-key project, and yet the team did not have the luxury of time to explore many alternative approaches or calibrate methods with deep-sea tests using known fluxes of fluids in prescribed ratios. A key parameter was the average ratio of gas to liquid. This term seemed to vary over the time period of the spill. Increasing gas increased the velocity of the plume but decreased the mass flow. Lacking independent estimates, the group took the average values provided by BP at face value. Analysis of the available short movies of the raiser flow shows the existence periods when the flow oscillates from pure gas to seemingly pure oil. This appears to be an indication of Slug Flow Regime. These periods of gas-oil flow fluctuation are in the range of minutes but could also be in the range of hours or even as long as days. In order to properly determine the effect of the intermittency of the gas/oil composition in the total estimate of the oil discharged from the riser leak, the analysis should be extended to long video records spanning several days.

Not all of the experts engaged in PIV analysis. Some simply reviewed the work of those that did, while still others provided additional verification by checking the PIV answers with their calculations using other techniques. 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. Some of these methods will be or are being examined in more depth by other groups. In all cases, the alternative estimate was consistent with the estimate produced by the PIV method. The appendices include further details on individual methods or preliminary results provided by members of the team. Please note that time constraints prevented the normal polishing and editing to these appendices.

APPENDICES

Appendix 1 describes briefly the credentials, provided by the individual, of each expert. The other appendices provide technical background information from individual experts.

- Appendix 2 – Deepwater Horizon Leak Estimation by Dr. Pedro Espina
- Appendix 3 - IPR-VLP graph for annular flow by Dr. Paul Bommer
- Appendix 4 – Analysis of the Intermittency of the Gas/Oil Composition Discharging from the Main Leak by Professors Lasheras, del Alamo, Aliseda, and Riley.
- Appendix 5 - PIV Analysis of BP Horizon Oil Leak Rate by the USDOE National Energy Technology Laboratory by Dr. Frank Shaffer
- Appendix 6 -Oil Flow Rate Analysis, Deepwater Horizons Accident by Dr. Steve Wereley
- Appendix 7 -Comments by Dr. Ira Leifer



APPENDIX 1 EXPERTS

The experts that reviewed this problem have varied but exceptional backgrounds, as demonstrated by their brief resumes given below. While the leading fluid dynamics experts were chosen, we also reached out to those in related fields such as petroleum engineering, oceanography and environmental engineering. Although government scientists were included in the team, they mainly provided a supportive role to the members from the academic community. These latter are the true heroes of this team. While some are receiving small consulting fees, most performed this herculean task gratis. Being called in many cases by a perfect stranger who asked them to drop their busy schedules and work on estimating a leak rate from a source one mile below the ocean, none refused.

I urge those reading this report to use the information in it for the purpose that it was intended. The numbers that the professors provided are only an estimate to assist the response. In this, they serve the same purpose as the earlier estimates of 1000 bbl and 5000 bbl. As more analysis is done and further data acquired, new estimates will be made, perhaps by some of these same experts. In the meantime, it has been my pleasure and honor to work with these gentlemen, who truly represent the finest of America's scholars.

William J, Lehr
Senior Scientist
NOAA Office of Response and Restoration
Plume Team Lead

EXPERTS BIOGRAPHICAL INFORMATION

Dr. Aliseda earned a B.S./M.S. in Aerospace Engineering from the Polytechnic University of Madrid, and his M.S. and Ph.D. in Mechanical Engineering from the Department of Mechanical and Aerospace Engineering at UCSD. During his doctoral research, he studied the interaction of drops and bubbles with a turbulent carrier flow. He did postdoctoral research in the MAE and BioE departments at UCSD for two years before joining the University of Washington. Since the fall of 2006, he has been assistant professor in the Mechanical Engineering Department at the UW. His current interests focus on turbulent and multiphase flows, including environmental problems such as cloud microphysics and marine renewable energy, and biomedical flows such as ultrasound contrast agents and vascular access for hemodialysis. In 2008, he was awarded the CAREER award by the National Science Foundation to study the dynamics of microbubbles in complex, unsteady flows.

Dr. Paul Bommer is currently a Senior Lecturer in the Department of Petroleum Engineering at The University of Texas at Austin. This position includes teaching courses in production engineering and drilling engineering. Responsibilities in this position also include directing a coordinated petroleum engineering program with the University of Trinidad and Tobago, and directing various guest student programs at The University of Texas.

Additionally he has 25 years of petroleum engineering consulting and oil and gas property operations experience. This includes the design and implementation of drilling and production programs in the US, evaluation and appraisal of hydrocarbon properties, field studies including secondary recovery operations, and expert witness work before state regulatory bodies and state and federal courts.

He holds a BS, MS, and PH.D. in petroleum engineering from The University of Texas. He is a registered professional engineer in Texas and a member of the Society of Petroleum Engineers and the American Association of Drilling Engineers.

Dr. Pedro I. Espina serves as Program Analyst at the Office of the Director of NIST, where he is responsible for, among other things, for the coordination of the NIST response to the Deepwater Horizon Incident. Prior to his current assignment, Dr. Espina served as the International Liaison of the International Bureau of Weights and Measures (BIPM) in Paris, where he helped coordinate international metrology. Dr. Espina also served a Scientific Advisor at the Chemical Science and Technology Laboratory of NIST, and he is the former Leader of the NIST Flow Metrology Group, the former Chair of the Metrology Working Group for Flow in the Inter-American Metrology System, and the former U.S. representative to the Working Group for Fluid Flow of the International Committee for Weights and Measures. Dr. Espina received his Ph.D. in Computational Fluid Mechanics from the University of Maryland in 1997.

Professor Lasheras is Stanford S. and Beverly P. Penner Professor of Engineering and Applied Sciences Distinguished Professor of Mechanical and Aerospace Engineering and Bioengineering at University of California at San Diego. Dr. Lasheras received his Doctorate from Princeton in Mechanical and Aerospace Engineering and Bachelor's in Science from Universidad Politecnica de Madrid. He is an expert on the structure and stability of turbulent mixing layers and jets, the mechanics of multi-phase turbulent flows, and regimes of liquid atomization. He is author of multiple scientific studies on turbulent two-phase flows and co-author of 42 US patents. He has won numerous awards, including Guggenheim Fellow, George Van Ness-Lothrop Fellow, F.N. Frenkiel Award for Fluid Dynamics, Elected Member of the Real Academia de Ingenieria de Espana (Royal Academy of Engineering of Spain), Elected Fellow of the American Physical Society and Chairman of the American Physical Society/Division of Fluid Dynamics.

Ira S. Leifer, Ph.D. Atmospheric and Oceanic Sciences, is world-renowned researcher in the Marine Sciences Institute with laboratory in the Ocean Engineering Laboratory of the Engineering Research Center at the University of California in Santa Barbara. He is widely published in several fields, with over 60 articles published in peer reviewed scientific journals. Most recently, Dr Leifer has served as the Chief Coordinating Mission Scientist for the Joint NASA/NOAA/USGS mission to use airborne remote sensing as part of the Macondo spill incident response.

Dr. Leifer's research begin with study of the ocean's interface with the atmosphere, and has expanded to included methane and hydrocarbon plumes in the ocean, in the atmosphere, methane hydrate research, remote sensing of hydrocarbons, and sub-sea monitoring of

methane emissions and other subsea activities. His experiments range from studies of the Santa Barbara methane seeps, to Arctic studies off Russia and Norway, to seabed methane clathrate field studies in the Gulf of Mexico 10 km from the recent Macondo well incident as recently as 2009.

He has developed innovative new technologies including second-generation pneumatic "bubble" booms to respond to oil in challenging conditions where traditional booms fail, 3D sub-sea scanning sonar systems (ROSScan), ROV tools, and passive acoustic monitoring systems. His research has been sponsored and coordinated with leading institutes of research and commerce (in random order): Aerospace Corp, Univ of Bremen, California DFG, California OSPR, California State Land Commission, Clean Seas, ENI, NASA, JAXA (Gosat), JPL, MBARI, MMS, Naval Research Labatory, NOAA CINMS, NOAA HazMat, , Scripps Institute (passive bubble/cetacean acoustics), SINTEF, STATOIL, TNO-FEL, University of Washington (ocean methane seepage), UCEI, and UC MEXUS. Dr. Leifer's research and innovations have been covered by CNN, the BBC, and educational programs in Europe and the U.S.A.

Jim Riley, the PACCAR Professor of Engineering at the University of Washington, is a fluid dynamicist whose research and teaching emphasize transitioning and turbulent flows. He has worked extensively on a broad range of problems, and is considered a pioneer in the development and application of direct numerical simulation to transitioning and turbulent flows.

At the University of Washington Riley is a Professor in the Department of Mechanical Engineering, and an Adjunct Professor in the Department of Applied Mathematics. He is a Fellow of the American Physical Society, and is a past Chair of its Division of Fluid Dynamics. He is also a Fellow of the American Society of Mechanical Engineers and a Fellow of the Institute of Physics.

Among his editorial responsibilities, Riley is an Associate Editor for the Journal of Fluid Mechanics, is a member of the Editorial Committee for the Annual Review of Fluid Mechanics, is an Associate Editor for the Applied Mechanics Reviews, and is also an Associate Editor for the Journal of Turbulence.

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Dr. Savas is an experimental fluid dynamist in the Mechanical Engineering Department of the University of California at Berkeley. He obtained his BS degree in Mechanical Engineering from the Middle East Technical University, Turkiye, and his MS and PhD degrees in Aeronautics from the California Institute of Technology. His has done reseach and published numerous peer reviewed papers in turbulent flows, rotating flows, combustion, vortex dynamics, aerodynamics, aircraft wake turbulence, rotorcraft dynamics, biofluid dynamics, instrumentation, wave energy conversion. He has developed numerous measurement techniques. His a fellow of the American Physical Society, an Associate Fellow of American Institute of Aeronautics and Astronautics, and A.D. Welliver Fellow of The Boeing Company

Franklin Shaffer is a Senior Research Engineer with USDOE National Energy Technology Laboratory. He holds BS and MS degrees in Mechanical Engineering from West Virginia University in 1984 and 1986. For 25 years he has led development of new high speed particle

image velocimetry (PIV) tools to study particle flow dynamics of energy processes. He has published extensively in this field and given invited seminars on high speed PIV in the US and Europe. His patented high speed PIV tools have also been widely applied in the development of medical devices. He has received numerous national and international awards for development of new high speed imaging tools, including the R&D 100 Award and the Federal Laboratory Award for Excellence in Technology Transfer.

Professor Steve Wereley completed his masters and doctoral research at Northwestern University studying Taylor-Couette flows as filtration aids. He joined the Purdue University faculty in August of 1999 after a two-year postdoctoral appointment at the University of California Santa Barbara. During his time at UCSB he focused exclusively on developing diagnostic techniques for microscale fluid systems, work which ultimately led to developing, patenting, and licensing to TSI, Inc., the micro-Particle Image Velocimetry technique. His current research interests include designing and testing microfluidic MEMS devices, investigating biological flows at the cellular level, improving micro-scale laminar mixing, and developing new micro/nano flow diagnostic techniques. Professor Wereley is very active in the field of micro/nanoscale fluid mechanics, delivering invited lectures, short courses and consulting, in addition to performing scholarly research in the area. Professor Wereley is the co-author of Fundamentals and Applications of Microfluidics (Artech House, 2002 and 2006) and Particle Image Velocimetry: A Practical Guide (Springer, 2007). He is on the editorial board of Microfluidics and Nanofluidics Journal and Experiments in Fluids and is an Associate Editor of ASME's Journal of Fluids Engineering. Professor Wereley has edited Springer's recent Encyclopedia of Microfluidics and Nanofluidics and Kluwer's BioMEMS and Biomedical Nanotechnology.

Dr. Poojitha Yapa, a Professor of Civil and Environmental Engineering at Clarkson University, Potsdam, NY has B.Sc in Civil Engineering and M.Sc in Hydraulic engineering. He received his Ph.D. in Civil and Environmental Engineering from Clarkson University in 1983. His research has focused on "environmental hydraulics problems". After initially working on river ice problems he moved to work on oil spill problems. For the last 25 years his research has been focused on oil spill modeling. This includes not only trajectory modeling, but modeling physico-chemical processes oil undergo when spilled in the ocean or rivers. In the last 15 years his modeling has been on deepwater oil, gas, and hydrates, studying the complex processes they undergo during the travel from deepwater to the surface. Dr. Yapa and his students developed a computer model (CDOG) for modeling the behavior of oil and gas when released in deepwater. The work has been published in leading journals.

Dr. Yapa received prestigious Erskine fellowship from New Zealand and Gledden Fellowship from Australia for long term visits to their Universities. He has also been invited to Universities in Japan. He has given nearly 50 invited seminars in 8 countries. He has numerous publications in leading Hydraulic Engineering and research journals and has been the associate editor of hydraulic journals of American Society of Civil Engineers (ASCE) as well as the International Association of Hydraulic Research (IAHR). Dr. Yapa chaired the Task Committee on Modeling of Oil Spills formed by the ASCE. He was a member of the advisory committee to NOAA on GNOME Model. At present he is a member of Task Committee on Best Practices in Oil Spill Modeling, CRRC/NOAA.

Deepwater Horizon Leak Estimation

On April 20, 2010, the Deepwater Horizon offshore oil drilling platform exploded and two days later, it sunk 40 miles (64.4 km) southeast of the Louisiana coast. As a consequence of this incident, an underwater oil leak resulted, originating from a number of sites at a depth of about 5,000 feet (1,524 m). Numerous estimates have been made for the amount of oil being discharged, ranging from over 1,000 barrels (42,000 US gallons; 158,987 liters) to more than 100,000 barrels (4,200,000 US gallons; 15,898,729 liters) of sweet, light crude oil per day. A more accurate determination of the magnitude of the oil spill is of interest. This note discusses how various parameters affect the estimation of the oil spill and attempts to bound the uncertainty in this estimation.

It is believed that oil is leaking from a number of sites at the bottom of the ocean including the end of the drilling riser. However, this note focuses on the estimation of the flow leaking from a fissure on top of the drilling riser (i.e., the bent pipe just above of the blowout preventer, BOP).

Video from remotely operated underwater vehicles (ROVs) shows a turbulent gas/liquid jet rushing out of a fissure on the central portion of the drilling riser bent above the BOP (see Figure 1). In this jet, the fluid is believed to be a mixture of crude oil and gas/hydrates (the gas being mostly methane). From the three leaks at the location viewed in the video, this analysis focuses on the leak in the center of the drilling riser, as it is believed to the most significant based on visual inspection of the video.

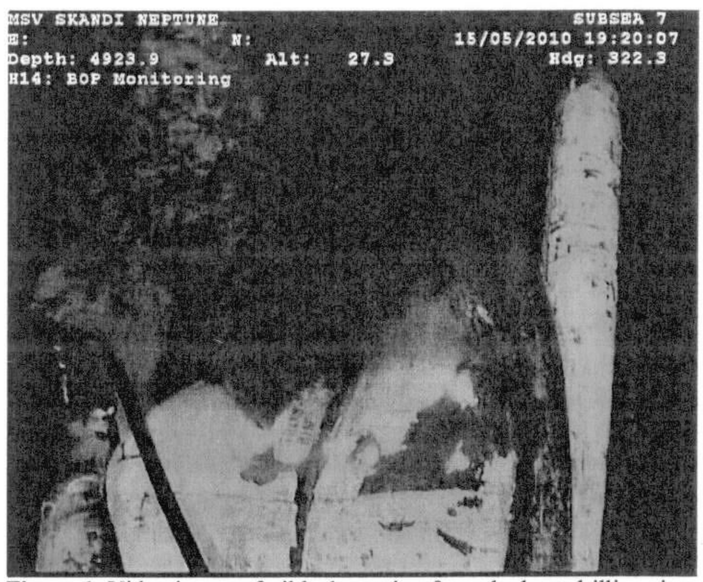


Figure 1. Video image of oil leak coming from the bent drilling riser just above the BOP. Three leaks are observed – this analysis focuses on the jet rushing out of the fissure next to the lettering at the center of the pipe.

If a number of parameters are measured and others approximated, an estimate of the flow of that jet can be performed using particle image velocimetry (PIV). In this method, a flow event in the leaking oil plume (e.g., an eddy in the flow) is observed in two consecutive video frames and its traveling velocity is estimated by dividing the distance traveled by the event, by the time between the two video frames. If this analysis is performed in a sufficiently large number of spatially- and time-distributed events, an average velocity of the leak jet can be adequately estimated. This note examines this methodology for the estimation of the oil leak and tries to assess it measurement uncertainty.

The average oil leak at this location, $\overline{Q}_{oil}$, can be estimated using the following expression,

$$\overline{Q}_{oil} = \overline{\overline{V}_{PIV} A_{PIV}}\, \overline{X}_{oil} \pm U_{\overline{Q}_{oil}} \quad (1)$$

where, $\overline{V}_{PIV}$ is the average velocity of the oil jet estimated using PIV, A_{PIV} is the average cross-sectional area of the jet at the location where the velocity of the jet was measured using PIV, and $\overline{X}_{oil}$ is the average volume fraction of oil in the jet (i.e., the fraction of the jet that is not gas and/or hydrates). Equation (1) will yield an estimate of the oil leak at the selected location (e.g., in barrels of oil per day, BPD) with an uncertainty, $\pm U_{\overline{Q}_{oil}}$, also expressed in BPD. It is worth noting than in (1), the product $\overline{\overline{V}_{PIV} A_{PIV}}$ is averaged over the ensemble of PIV observations made (more on this later in this note).

If a flow feature in the jet exiting from the fissure on top of the bent drilling riser is selected from the video, it will be observed to travel a distance L'_{12} in the time between two consecutive video frames, Δt_{12}. But unless the travel path of the event is viewed from an orthogonal plane, the true distance travelled by the flow event, L_{12}, will be larger than the observed distance L'_{12}. The relation between the observation and the reality will be given by,

$$L_{12} = \frac{L'_{12}}{\cos\alpha_{12}} \quad (2)$$

where, α_{12} is the angle by which the video camera is off a perfectly orthogonal view of the jet. Using the above, the velocity of an observed event, i, will be given by,

$$\left(V_{12}\right)_i = \frac{\left(L_{12}\right)_i}{\left(\Delta t_{12}\right)_i} = \left(\frac{L'_{12}}{\Delta t_{12}\cos\alpha_{12}}\right)_i \quad (3)$$

It is the opinion of the expert team that $\alpha_{12} \le 5^\circ$, making this error insignificant in this analysis (further details in the uncertainty section below). But it is worth noting that if the video camera view is assumed to be perfectly orthogonal, that is to say $\alpha_{12} = 0$ (i.e., best case scenario), the flow of oil coming out of the jet is likely to be underestimated. In addition, there are instances when the ROV changes location as it is filming the jet or when the operator of the video camera zooms in or out in the view and/or changes focus. These changes cause two problems in the interpretation of the PIV results. First, these filming disruptions might add an apparent velocity to the PIV measurements, and second, they might change the coordinate system in the images relative to the jet (i.e., will change α_{12}). Fortunately, the error due to these effects can be minimized by selecting portions of video where no ROV drift and/or changes in the viewing parameters of the video camera appear to be present.

The observed travel distance of a flow event, L'_{12}, is determine by inspection in the video frames. For physical scaling in the video images, BP provided the exterior diameters of a number of pipes in the video field of view:

- that of the black pipe entering the frame from the bottom left hand side = 1.22 inches (30.48 mm), and

- that of the grey pipe entering the frame from the bottom right = 3.5 inches (88.90 mm).

Using these numbers and interrogating the video at an equivalent depth of field to the apparent axis of the jet (i.e., the diameter of the pipes near the center of the video window), we find that the black pipe is about 18.4 pixels in diameter and the grey pipe is about 44.4 pixels in diameter. As a result, each pixel is likely to represent a distance between 0.0665 inches (1.69 mm) and 0.0788 inches (2.00 mm). Thus, under the best of cases, the distance traveled by a flow feature could at best be estimated to ±1 pixel or with an uncertainty, $U_{L'_{12}} = \pm 0.0725$ inches (1.84 mm). However, due to the turbulent nature of the jet, the main source of uncertainty in the determination of L'_{12} is likely to be the visual inspection made by the evaluator, which for the purposes of this analysis we assume to be $U_{L'_{12}} / L'_{12} = \pm 5\%$.

The time between video frames, $(\Delta t_{12})_i$, can be obtained from the framing rate of the video, FR_i. The video acquired by the ROV is analog and it has been digitized for the purposes of this study. Inspection of the video reveals that the framing rate of the digital video is not constant,[1] with framing rates in the range from 14 to 48 frames/second (fps). However, members of the expert team determined that the true framing rate of the analog video is 25 fps. Thus, for the purposes of the PIV analysis, $(\Delta t_{12})_i$ can be estimated with a measure of confidence to ±1 frame in that interval. That is to say,

$$(\Delta t_{12})_i = \frac{1}{FR_i \pm 1} \tag{4}$$

There are computer programs that can interrogate the available video for hundreds of such flow events, thus providing the ability for hundreds of observations in an adjacent pairs of video images. As a result, the space-averaged velocity of the jet in the observation window of the video for any two consecutive frames will be given by,

$$\overline{V}_{12} = \frac{1}{n}\sum_{i-1}^{n}(V_{12})_i \tag{5}$$

where n is the number of flow events considered in the averaging (i.e., this is a spatial average of the observed phenomena).

Because, the spatial and temporal distributions of the selected flow events could greatly influence the average yielded by (**5**), care should be taken to ensure that the ensemble of events considered is representative. In addition, the procedure described above does not constitute PIV in the traditional sense, where small particles that faithfully follow the flow are tracked. Rather, the procedure described above tracks flow features in the shear layer of the jet that might move at lower speeds. This effect is likely to lead to an <u>underestimation</u> of the oil flow in this leak.

[1] BP provided video in file name "H14 BOP Plume May 15 1920-1945.asf" depicting the flow on top of the BOP. The video appears to have been recorded on 15/05/2010 between 19:20 and 19:45. The original analog video was acquired by the ROV NSV Skandi Neptune at a reported depth of about 4924 ft below sea level.

Because oil is opaque, the video camera can only see events occurring in the outer edge of the jet (i.e., its shear layer) where the velocity is less than in the core of the jet. The relationship between the observed velocity in the jet shear layer and the jet average velocity can be estimated using correlations for turbulent jets in the literature. However, if $\overline{V}_{12}$ is taken to be the average velocity of the jet at the observation site (i.e., $\overline{V}_{12} = \overline{V}_{PIV}$), the flow in the oil jet is likely to be underestimated.

The average cross-sectional area of the jet at the location where its velocity was measured, A_{PIV}, can be determine from a direct interrogation of the video frames used during the $\overline{V}_{PIV}$ estimation. This area has to independently evaluated for each $\overline{V}_{PIV}$, thus the average of their product is given by,

$$\overline{\overline{V}_{PIV} A_{PIV}} = \frac{\pi}{4m} \sum_{j=1}^{m} \left(\overline{V}_{PIV}\right)_j \left(d_{PIV}^2\right)_j \tag{6}$$

where $\left(d_{PIV}\right)_j$ is the observed diameter of the jet at each of the m instances when $\overline{V}_{PIV}$ was evaluated (i.e., this is a temporal average of the observed phenomena). As it was the case for L_{12}, the relation between the observation and the reality will be given by,

$$d_{PIV} = \frac{d'_{PIV}}{\cos \alpha_{12}} \tag{7}$$

where, α_{12} is the angle by which the video camera is off a perfectly orthogonal view of the jet. As with L'_{12}, d'_{PIV} could be estimated to no better than ±1 pixel or ±0.0725 inches. However, due to the turbulent nature of the jet shear layer, the main source of uncertainty in the determination of d'_{PIV} is likely to be the visual inspection made by the evaluator, which for the purposes of this analysis we assume to be $U_{d'_{PIV}} / d'_{PIV} = 5\%$.

The jet spilling from the fissure at the top of the drilling riser above the BOP is believe to be a mixture of gas and oil, that is to say, the brown plume view in the video is composed of oil with bubbles of gas and/or hydrates entrained in it. The concentration of entrained gas in the oil can be expressed in terms of a gas to oil ratio, $\mathcal{V}_{gas} / \mathcal{V}_{oil}$, where $\mathcal{V}_g$ is the volume of gas/hydrates entrained in the volume of liquid oil, $\mathcal{V}_l$. The gas to oil ratio could be estimated from sampling measurements or by other means, and it fact, it has been estimated twice:

- reported by BP (during the May 22, 2010 expert group conference call) – 3000 standard cubic feet of gas per barrel of oil [scf/bbl], based on their collection of recovered spill at the surface, and
- reported by the Coast Guard (on May 23, 2010) – 3000 scf/bbl, based on their recovery of spill oil from the riser insertion tube (RIT, i.e., the siphon sucking at the end of the broken drilling riser).

During the expert conference call on May 22, 2010, BP claimed that their estimate of gas to oil ratio was "pretty good" and when pressed for a number, "no worst than ±10 %"; the Coast Guard made no uncertainty claims in their gas to oil ratio estimate. These values are equivalent and both were provided at ocean surface conditions. For these values to be useful to this analysis, they have to be converted to values at the leak site. Using the ROV

reported depth (approximately 5000 ft under sea level) and the BP reported ocean temperature at the leak site (1° C), the average volume fraction of oil in the jet, $\overline{X}_{oil}$, is given by

$$\overline{X}_{oil} = \frac{\forall_{oil}}{\forall_{oil} + \forall_{gas}} = \frac{1}{1 + \left(\forall_{gas} / \forall_{oil}\right)} \tag{8}$$

or 0.29 [2] with a relative uncertainty of ±10 % based on the reported values above. However, members of the expert team, estimated by other means the average volume fraction of oil in the jet to be 0.25 – the value use in this analysis. This value not only accounts for the distribution of gas/hydrates in the leaking jet but also for its temporal fluctuations over long periods of time. Given the critical nature of this value to this calculation and the poor sources of data used to arrive at it, we are giving it a conservative uncertainty value, $U_{\overline{X}_{oil}} / \overline{X}_{oil} = 40\%$.

It is worth noting that if the jet flow is assumed to have no entrained gas/hydrates (i.e., $\overline{X}_{oil} = 1$), the flow of oil coming out of the leak over the bent riser on top of the BOV will be overestimated.

Using the above analysis, the estimates of the average oil leak from a fissure on top of the drilling riser, $\overline{Q}_{oil}$, can be bounded by an uncertainty of $\pm U_{\overline{Q}_{oil}}$. What follows are two limiting examples for the results from the expert team.

Uncertainty Analysis

For the purposes of the uncertainty analysis, can be simplified as,

$$\overline{Q}_{oil} = \overline{\overline{V}_{PIV} A_{PIV}} \overline{X}_{oil} \approx \overline{V}_{PIV} A_{PIV} \overline{X}_{oil} = \frac{L'_{12}}{\Delta t_{12} \cos\alpha_{12}} \frac{\pi}{4} \left(\frac{d'_{PIV}}{\cos\alpha_{12}}\right)^2 \overline{X}_{oil} \tag{9}$$

Thus the relative uncertainty in $\overline{Q}_{oil}$ can be expressed as

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = \begin{array}{c} \left(\frac{L'_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial L'_{12}}\right)^2 \left(\frac{U_{L'_{12}}}{L'_{12}}\right)^2 + \left(\frac{\Delta t_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \Delta t_{12}}\right)^2 \left(\frac{U_{\Delta t_{12}}}{\Delta t_{12}}\right)^2 + \left(\frac{\alpha_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \alpha_{12}}\right)^2 \left(\frac{U_{\alpha_{12}}}{\alpha_{12}}\right)^2 + \\ \left(\frac{d'_{PIV}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial d'_{PIV}}\right)^2 \left(\frac{U_{d'_{PIV}}}{d'_{PIV}}\right)^2 + \left(\frac{\overline{X}_{oil}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \overline{X}_{oil}}\right)^2 \left(\frac{U_{\overline{X}_{oil}}}{\overline{X}_{oil}}\right)^2 \end{array} \tag{10}$$

where the sensitivity coefficients are given by

$$\left(\frac{L'_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial L'_{12}}\right) = 1 \tag{11}$$

$$\left(\frac{\Delta t_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \Delta t_{12}}\right) = -1$$

---

[2] NIST REFPROP

$$\left(\frac{\alpha_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \alpha_{12}}\right) = -3\alpha \tan \alpha$$

$$\left(\frac{d^2_{PIV}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial d^2_{PIV}}\right) = 2$$

$$\left(\frac{\overline{X}_{oil}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \overline{X}_{oil}}\right) = 1$$

and the relative uncertainties of each of the components are summarized in the text above and are given by,

$$\left(\frac{U_{L'_{12}}}{L'_{12}}\right) = \pm 0.05$$

$$\left(\frac{U_{\Delta t_{12}}}{\Delta t_{12}}\right) = \pm\frac{1}{25+1} = \pm 0.038 \qquad (12)$$

$$\left(\frac{U_{d'_{PIV}}}{d'_{PIV}}\right) = \pm 0.05$$

$$\left(\frac{U_{\overline{X}_{oil}}}{\overline{X}_{oil}}\right) = \pm 0.4$$

Therefore the relative uncertainty of $\overline{Q}_{oil}$ is

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = (1)^2(0.05)^2 + (-1)^2(.038)^2 + (-3\alpha\tan\alpha)^2\left(\frac{U_{\alpha_{12}}}{\alpha_{12}}\right)^2 + (2)^2(0.05)^2 + (1)^2(0.4)^2 \qquad (13)$$

For $\alpha_{12} \leq 5^\circ$, the uncertainty related to this angle becomes insignificant (less than 5 % of the total uncertainty) and thus can be ignored. As a result the relative uncertainty in the estimation of the flow from the leak on top of the BOV is no larger than,

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = \pm 41\% \qquad (14)$$

And this value is dominated, in a disproportional way, by the gas to oil ratio estimate. If the gas to oil ratio was know better, e.g., ± 20 %, the oil leak uncertainty would drop to ±22 %.

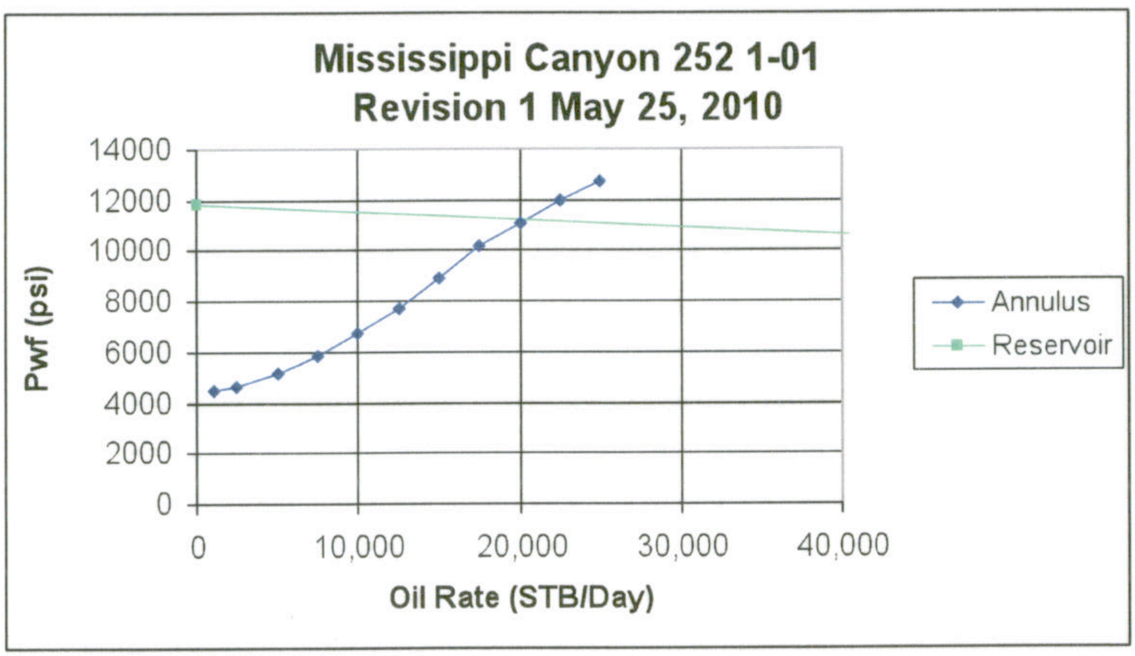
Appendix 3 by Paul Bommer

Memo

To: Bill Lehr
From Paul Bommer
Date: May 26, 2010

Re: IPR-VLP graph for annular flow (latest BP data set)

The maximum escape rate out the annulus is 20,000 STBO/day – unconfined by the kink in the riser.



Appendix 4

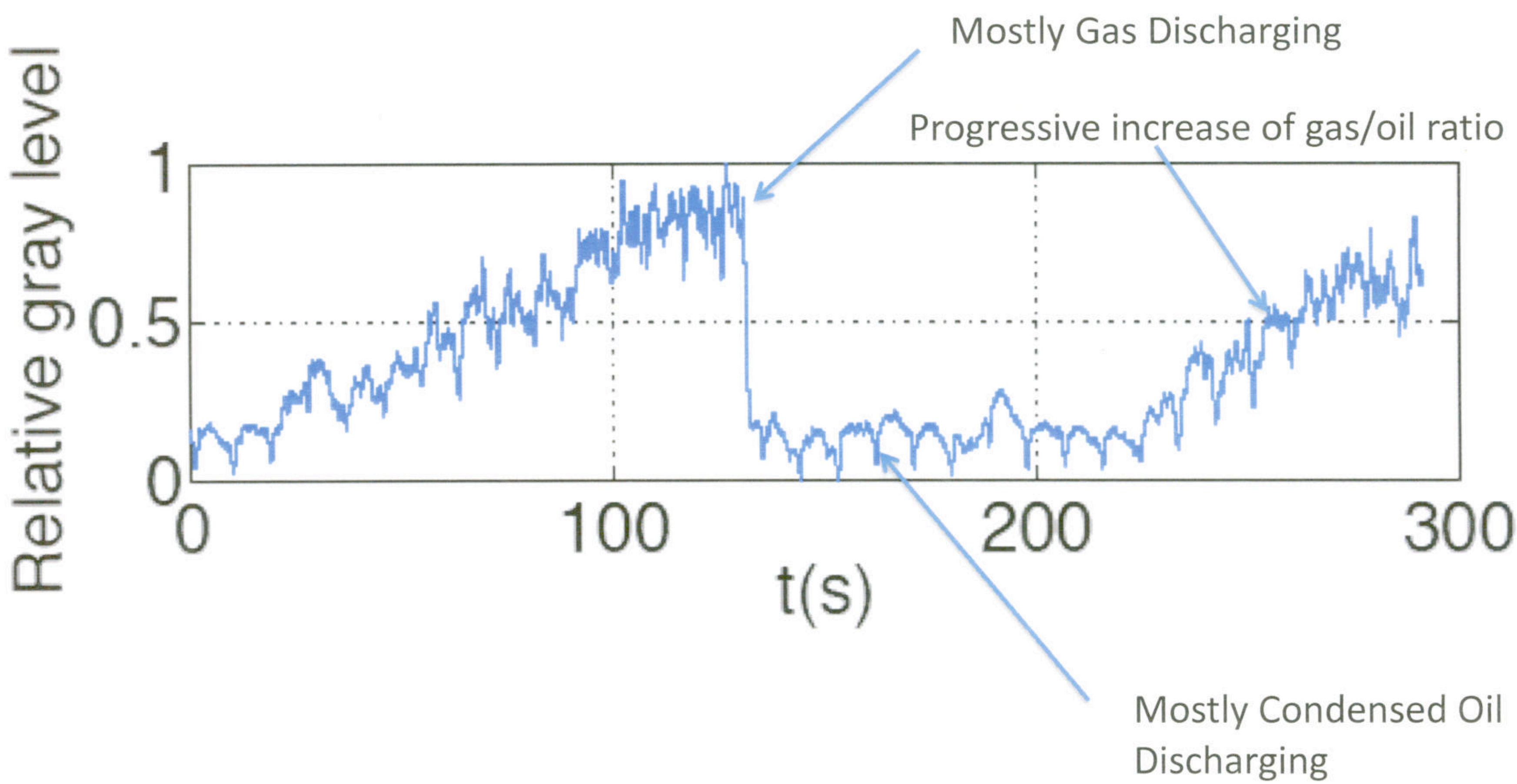
Analysis of the Intermittency of the Gas/Oil Composition Discharging from the Main Leak

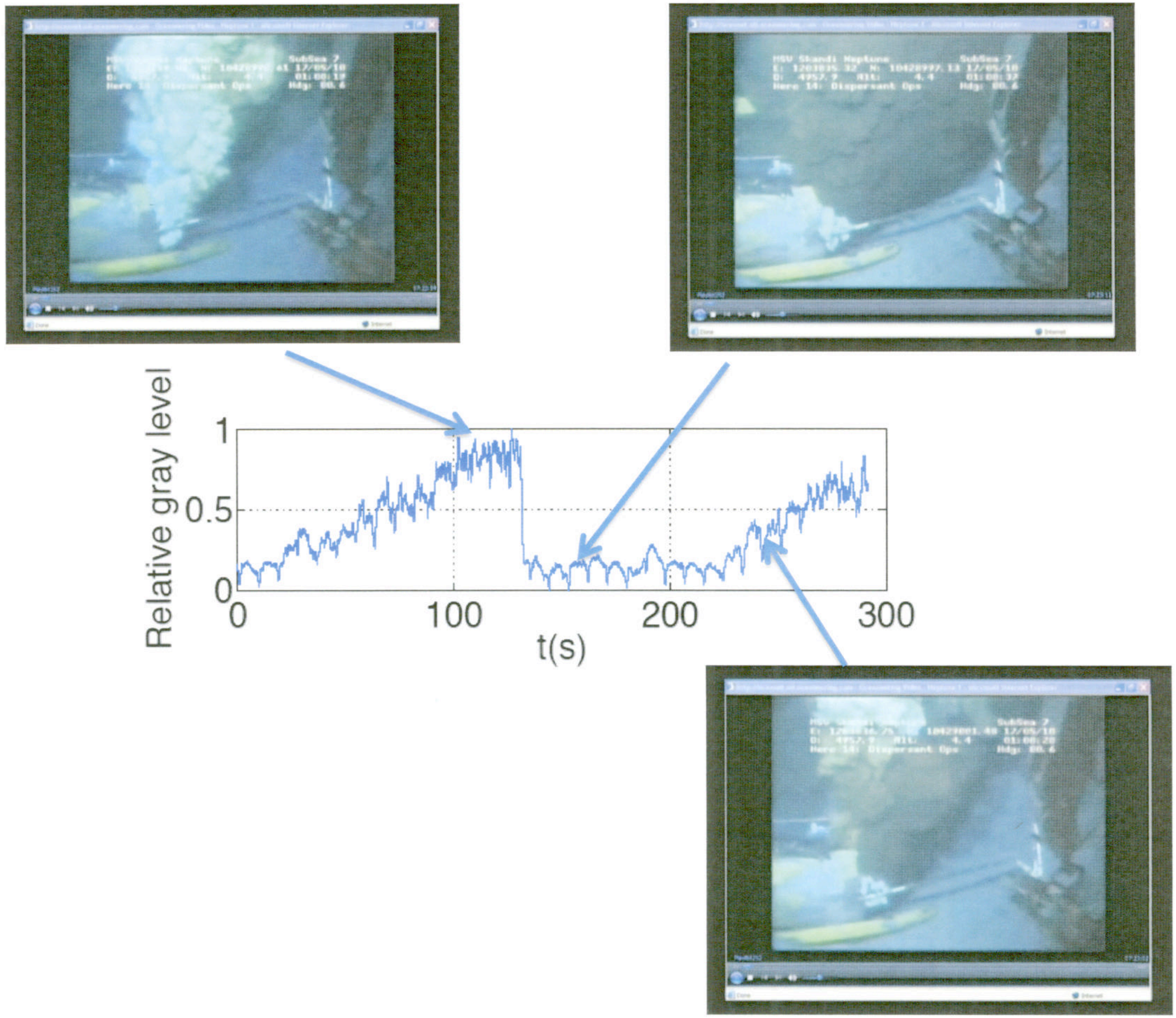
Juan C. Lasheras and Juan C. Del Alamo
University of California San Diego
Alberto Aliseda and James Riley
University of Washington

- **video 051720101304crater.mpg,**
- **5 minutes only!**
- The gas-oil flow is highly intermittent with
- a) events dominated by almost pure gas (made evident not only by the sharp change in brightness, but more importantly by the fact that the jet becomes buoyancy-driven with a sharp parabolic shape rising upward);
- b) events dominated by what seems almost pure condensed oil (this is evident by the change to an almost uniform dark color, and more importantly by the fact that the jet is then mainly momentum-driven and discharges almost horizontally with a very small parabolic curvature (these are the events analyzed by Steve Wereley); and
- c) events where a mixture of gas and oil is discharged simultaneously.
- To be able to measure the oil discharged from these images, we need to estimate with sufficient statistical significance the time of these events, and the fraction of oil being discharged at each time.

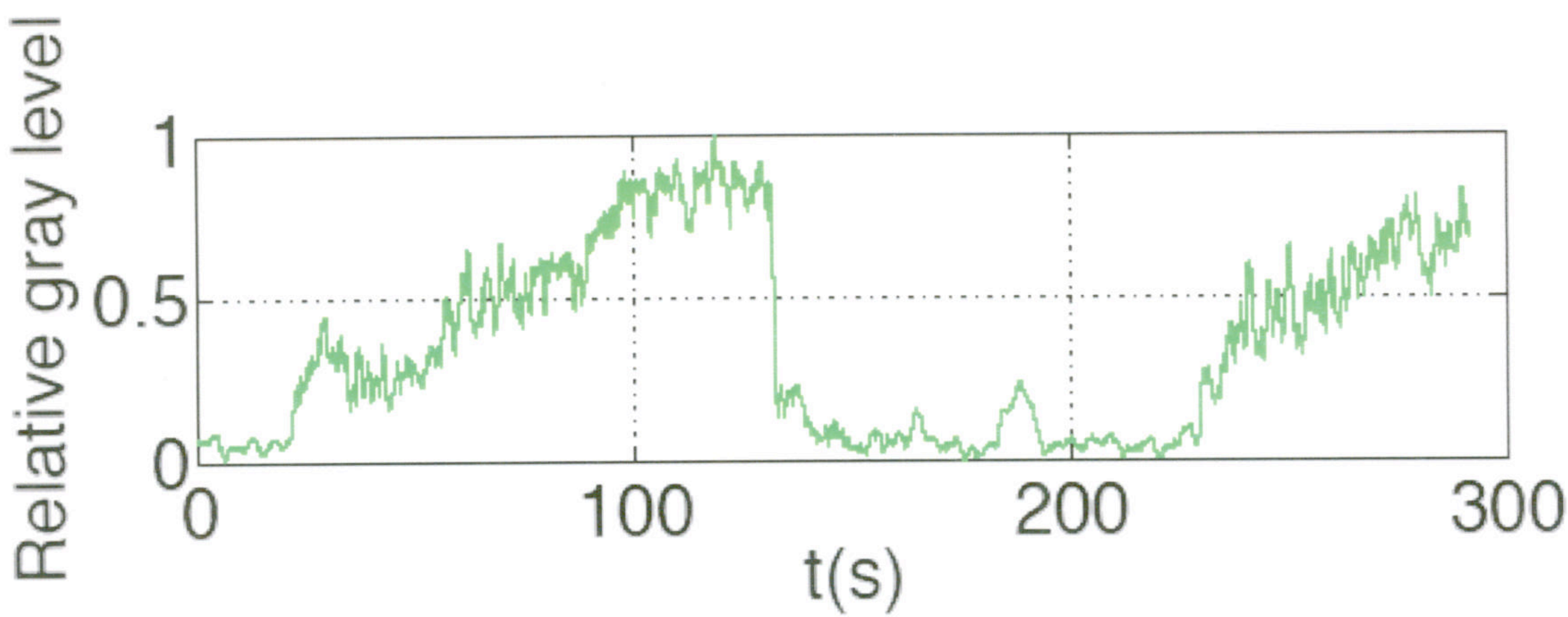
Measuring the time variation of the average image brightness in the region highlighted in the figure allows for the determination of the intermittency of the gas/oil flow rate

Observe the presence of two distinct periods of flow oscillations: a short period of approximately 10 seconds, and a longer period of 2 – 3 minutes

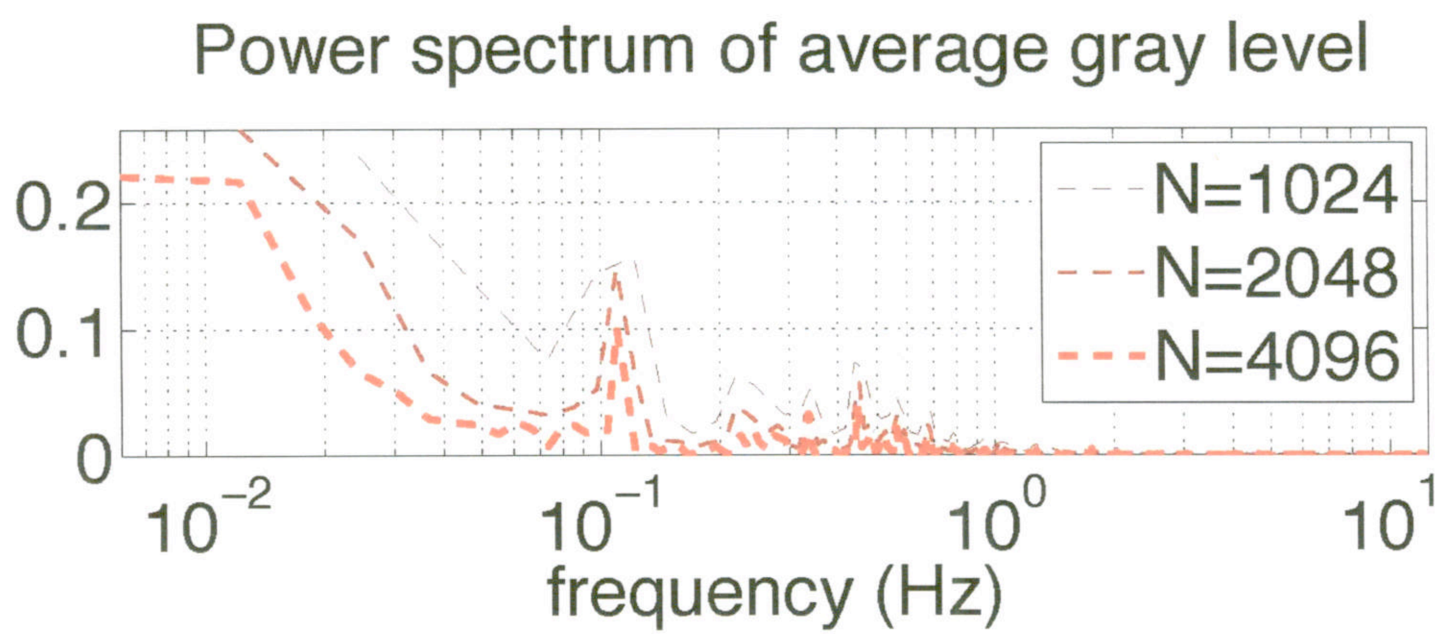



Relative gray level
1
0.5
0
0
100
200
300
t(s)

The standard deviation shows the same longer 2 to 3 minute period



The spectrum of the jet's composition exhibits a very well defined 10 second period



Conclusion

- **The gas/oil mixture discharging from the main pipe is highly intermittent**.
- Analysis of the short 5 minute video taken on May 17^{th} 051720101304crater.mpg shows the existence of two well defined periods: a short 10 second period and a longer 2 to 3 minute period when the flow oscillates from pure gas to seemingly pure oil. This appears to be an indication of Slug Flow Regime.
- **There may be even longer periods of gas-oil flow fluctuation in the range of hours or even as long as days that must be characterized.**
- **In order to properly determine the effect of the intermittency of the gas/oil composition in the total estimate of the oil discharged from the riser leak, the method outlined here should be applied to long video records spanning several days.**
- Current flow estimates based on PIV measurements should be corrected to account for the observed oscillations in the Gas/Oil composition by a factor of at least 50%.

Appendix 5

PIV Analysis of BP Horizon Oil Leak Rates by the USDOE National Energy Technology Laboratory

Frank Shaffer
USDOE National Energy Technology Laboratory
Office of Research and Development
Computational Science Division

This is a report submitted by the NETL to the Plume Calculation Team of the government's Flow Rate Technical Group (FRTG). The Plume Calculation Team is doing an independent analysis of the total oil leak rate from the BP Deepwater Horizon. The team is led by Bill Lehr of NOAA and Marcia McNutt, Director of USGS.

NETL was asked to use its unique high speed particle imaging velocimetry (PIV) tools to measure oil flow rates using videos of the oil leak jets. The videos were taken by BP's Remote Operation Vehicles (ROV) and a total of nine videos were supplied to the NETL. The videos are at reduced resolution of 720x480 pixels. The original BP video is 1600x1200 pixel resolution, but that was not available in time for this analysis.

The BP videos show two oil leak jets at the sea floor from the BP Deepwater Horizon. One leak is from the main riser on the sea floor and the other leak is from a bent riser pipe. NETL applied its proprietary (patent pending status) high speed PIV analysis tools to measure the velocity both oil leak jets. NETL's PIV velocity measurements are in agreement with three other independent PIV analyses done by different researchers on the Plume Analysis Team (Steve Wereley of Purdue; Alberto Aliseda of Univ. of Washington, and Ira Leifer, Marine Sciences Institute).

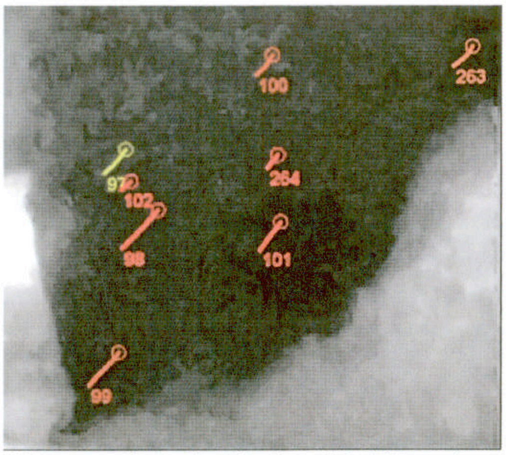
The Plume Analyis Team was charged with doing a quick analysis of the oil leak rate and produce a report describing the analysis. The report will be released by the White House on Thursday, May 27, 2010. The Plume Analysis Team operated with the understanding that time was not available to do a complete engineering analysis. The White House set a deadline of May 26 at 3:30 PM to deliver our independent estimate. NETL joined this activity only on May 24. The release by the White House will include a statement that the team's analyses are only a first estimate, and the numbers may be revised as more time, information, and analysis tools are available.

The NETL PIV analysis consisted of the following general steps:

1. A series of Fast Fourier Transform (FFT) highpass filters were applied to isolate small features of the oil jets shown in the BP videos
2. Maximum, median, and several other kernel filters were applied to dilate the small structures into circular images that resemble particle images

3. NETL's high speed particle imaging software was applied to track the trajectories of jet feature "particles," thereby measuring jet velocity along streaklines throughout the oil leak jets.

The two still images below are examples of the streaklines measured with NETL's PIV tools.



Close-up view of main riser jet. The colored lines show features in the main riser jet tracked by NETL's PIV tools. At this time, oil was flowing and no methane was observed.

View of the oil leak jets from the bent riser pipe. The colored lines show features in the jets being tracked by NETL's PIV tools. At this time, oil was flowing and no methane was observed.

Since at the time this analysis was done, BP had supplied the Plume Analysis Team with medium resolution videos (720 x 480 pixe0) only, and since the videos were not long enough to show significant variation in flow rate, if any existed, only brief segments of the videos were analyzed by NETL. Two hundred and fifty video frames were analyzed for the pipe bend leak and four hundred and sixty frames for the main riser jet.

Movies showing feature tracking by NETL's PIV software overlain on top of original BP videos were supplied to the team. These clearly show that oil leak rate can be measured from BP videos of the oil leak jets. Copies of these videos may be obtained by contacting the author at Franklin.Shaffer@netl.doe.gov

Total oil leak rate was calculated using the team's PIV measurements of jet velocities. Oil leak rate is directly proportional to jet velocity. The methodology for calculation of the total oil leak rate is included in the team's main report. Certain assumptions were made about the amount of water entrained into the oil jet and the velocity profile of the oil jet. These assumptions are explained in the main report.

Since NETL's PIV measurements of jet velocities are in good agreement with other independent PIV measurements by the team, NETL did not repeat the calculation of total oil leak rate, because the calculation would give the same numbers as given in the main report, namely, a minimum oil leak rate of 12000 to 25000 barrels per day. It should be noted that this is an estimation of the minimum oil leak rate.

It should be noted that it is possible that the actual minimum oil leak rates (and maximum rates which are not reported at this time by the Plume Analysis Team) are much higher than given in the May 27, 2010, report by the Plume Analysis. This is because the PIV analyses could only measure velocity on the outer surface of the oil leak jets. It is well known that such jets have velocity profiles in which the velocity is much higher in the center of the jet. If this velocity profile were accounted for in the calculation of oil flow rate, a much higher number could be produced. However, the Plume Analysis Team did not have time to accurately account for jet velocity profiles in the time given to produce an estimate. A jet flow expert at the NETL, Dr. Nate Weiland, did study the BP oil leak jet videos and performed initial estimations of the magnitude of the peak velocity at the center of a similar oil jet. Dr. Weiland estimates that the maximum velocity in the center of a similar oil jet could be an order of magnitude higher than the velocity at the outer edge of the jet. This could significantly increase the estimation of both minimum and maximum oil leak rate.

NETL PIV Results supplied to the Plume Analysis Team:

- NETL's PIV analysis of the BP video of the oil leak jet from the pipe bend showed that velocities at the periphery of the oil jet are in the range of 0.7 m/s to 1.7 m/s. PIV measurements were achieved at a location 0.4 to 0.5 meters downstream of the jet exit.
- NETL's PIV analysis of the BP video of the oil leak jet from the main riser showed that velocities at the periphery of the oil jet are in the range of 0.1 m/s to 0.7 m/s. PIV measurements were achieved at a location 0.1 to 0.5 meters downstream of the jet exit.
- Videos were supplied to the Plume Analysis Team showing feature tracking by NETL's PIV software overlain on top of the original videos supplied by BP.

Appendix 6

Oil Flow Rate Analysis

Deepwater Horizons Accident

Steve Wereley

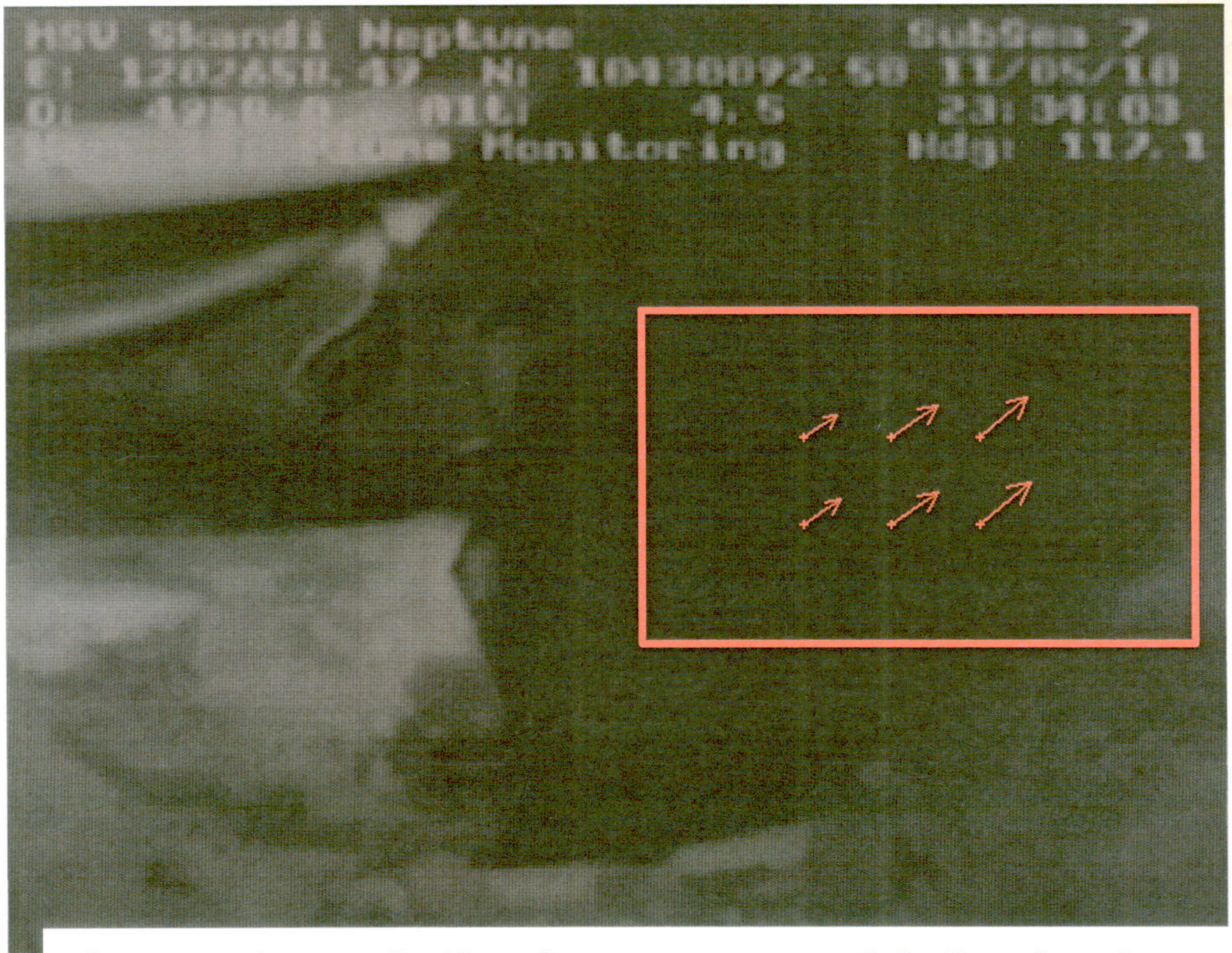
Professor of Mechanical Engineering
Birck Nanotechnology Center
Purdue University (USA)
wereley@purdue.edu

Manual Feature Tracking

Not rocket science—identify features in the image and see where they go as time elapses

Observed displacement: 11.7 pixels

Computer Analysis (PIV)



Calculated displacement: 10.2 pixels

PURDUE UNIVERSITY
Discovery Park

Convert to Barrels per Day

- Find average plume velocity

$$10.2\,\frac{pixels}{frame}\times\frac{1\,frame}{0.067\,sec}\times\frac{21in}{124pixels}=25.8\,\frac{in}{sec}$$

- Multiply by cross-sectional area to find volume flow rate

$$25.8\,\frac{in}{sec}\times\frac{\pi}{4}\times(20in)^2=8105\,\frac{in^3}{sec}$$

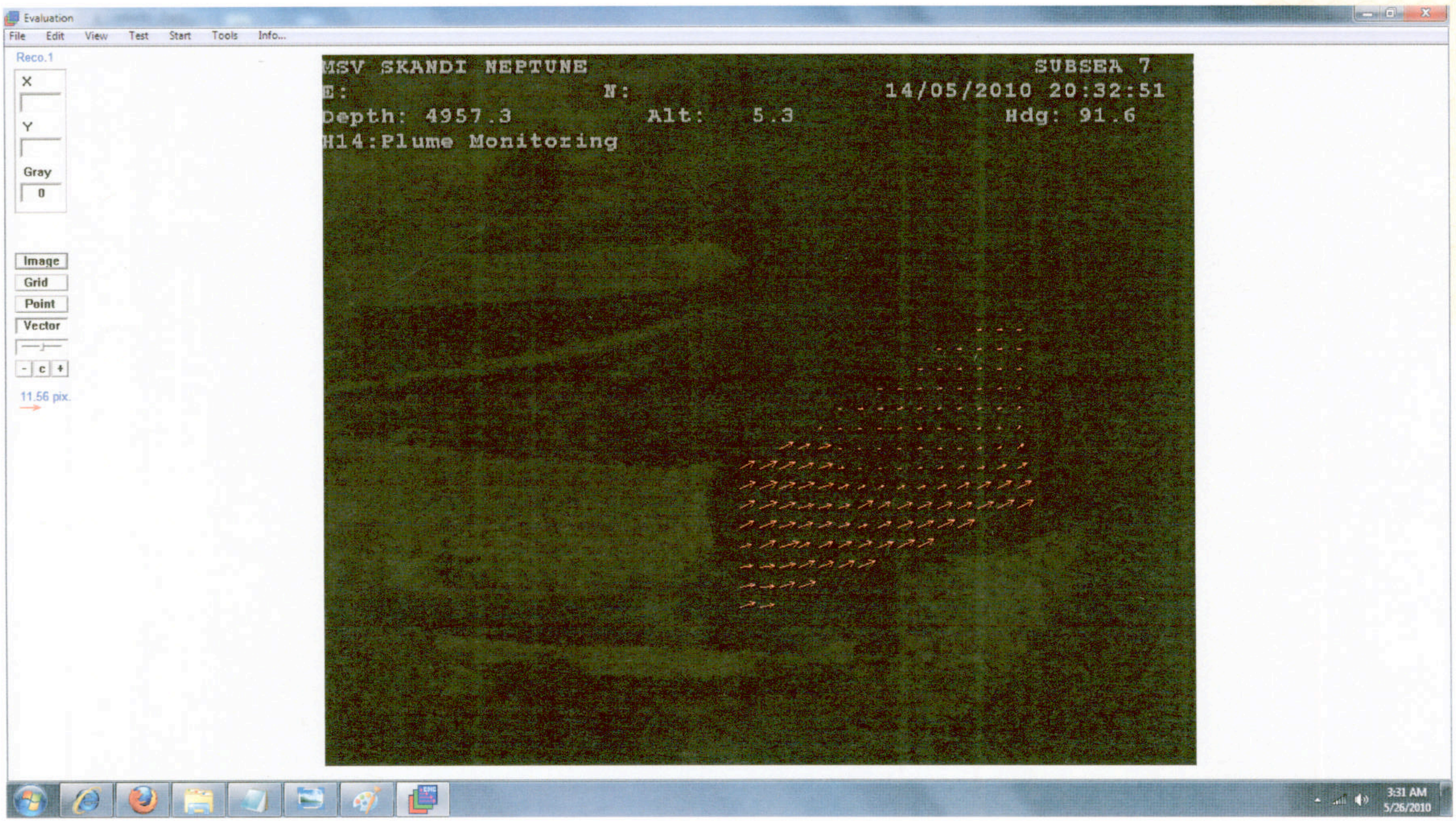
- Convert to barrels per day

$$8105\,\frac{in^3}{sec}\times\frac{60\times60\times24sec}{day}\times\frac{1gal}{231in^3}\times\frac{1bbl}{42gal}=\boxed{72179\,\frac{bbl}{day}}$$

May 14 2010 2024 H14 Riser End Plume 91 deg

- Analysis based on ensemble of 50 images
- Starting 516.007 secs from start of video
  - Clear observation of plume at that point
  - Mostly liquid flow
- Average velocity 36.8 in/sec (0.935 m/s)
- Plume diameter immediately outside pipe
  - 18.12 in
  - Accounts for 30% area reduction
  - Ignored drill pipe presence
- Total liquid flow: 84423 bbl/day

Velocity field



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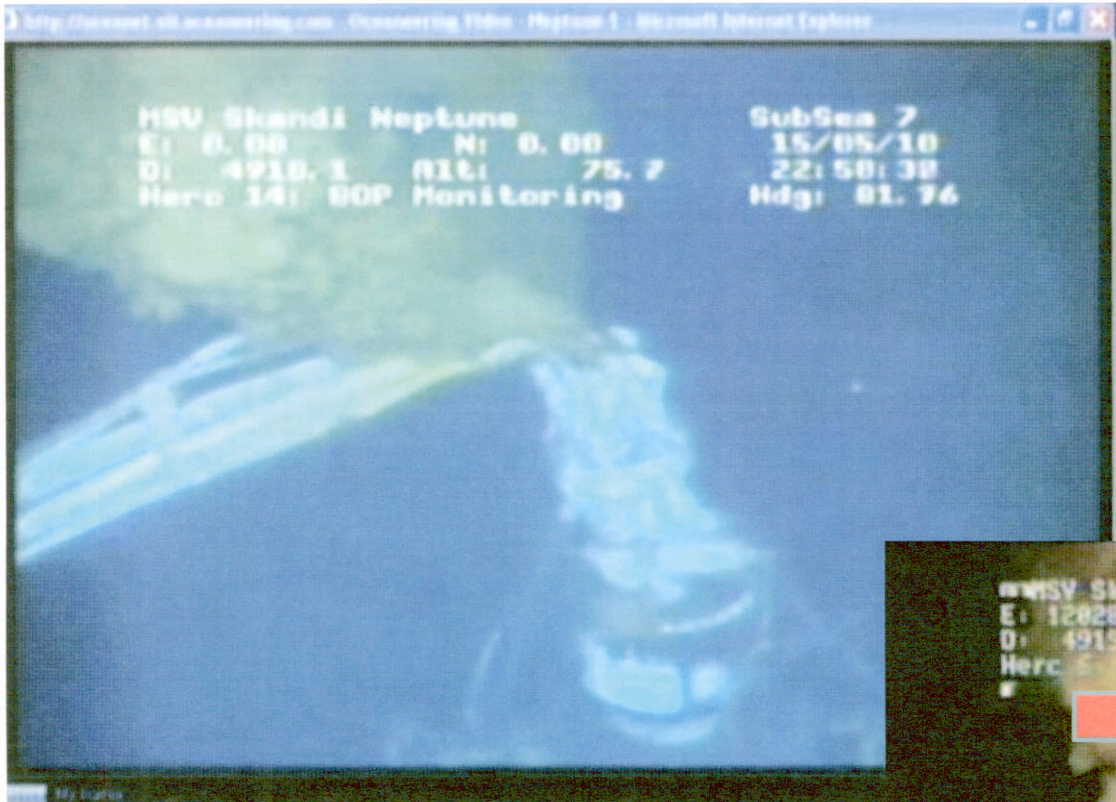
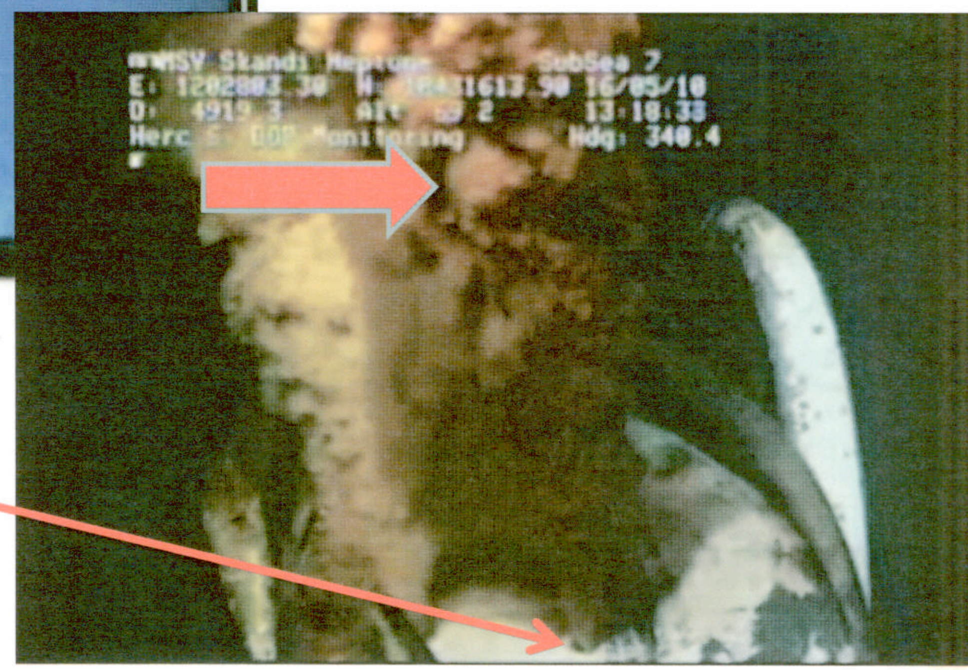
Flow at kink on top of BOP



Manual tracking:
Kink oil flow rate:
25,000 bbl/day
35% of riser flow



1.2 in hole

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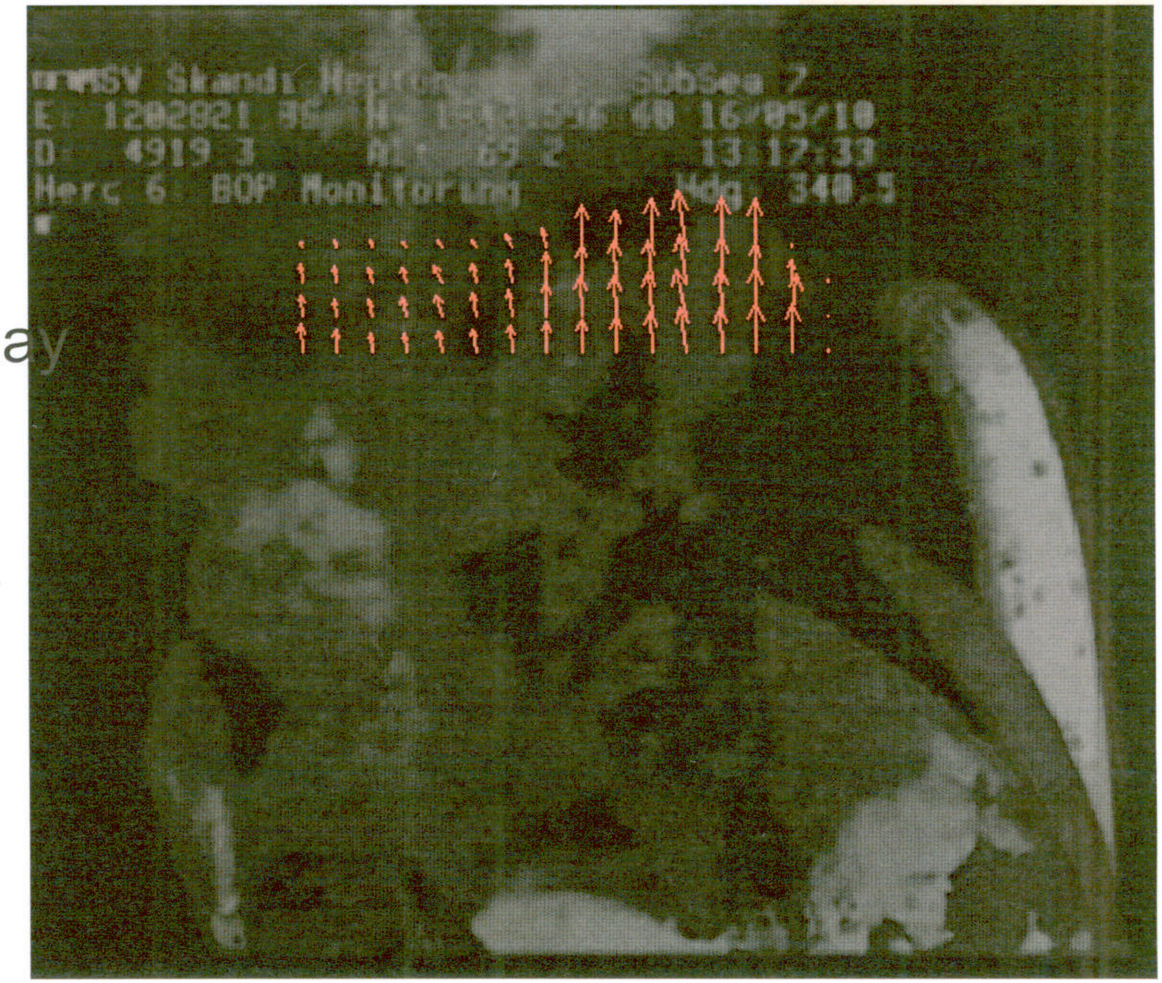
Discovery Park

Kink PIV

Avg disp: 10.7 pix
Avg vel: 10.3 in/sec
Jet diam: 192 pix
Jet Xsect: 121 in^2
Volume flow: 11,000 bbl/day



Total flow: 83,000 bbl/day
(gas + oil)
Oil (using BP's GOR):
41,500 bbl/day

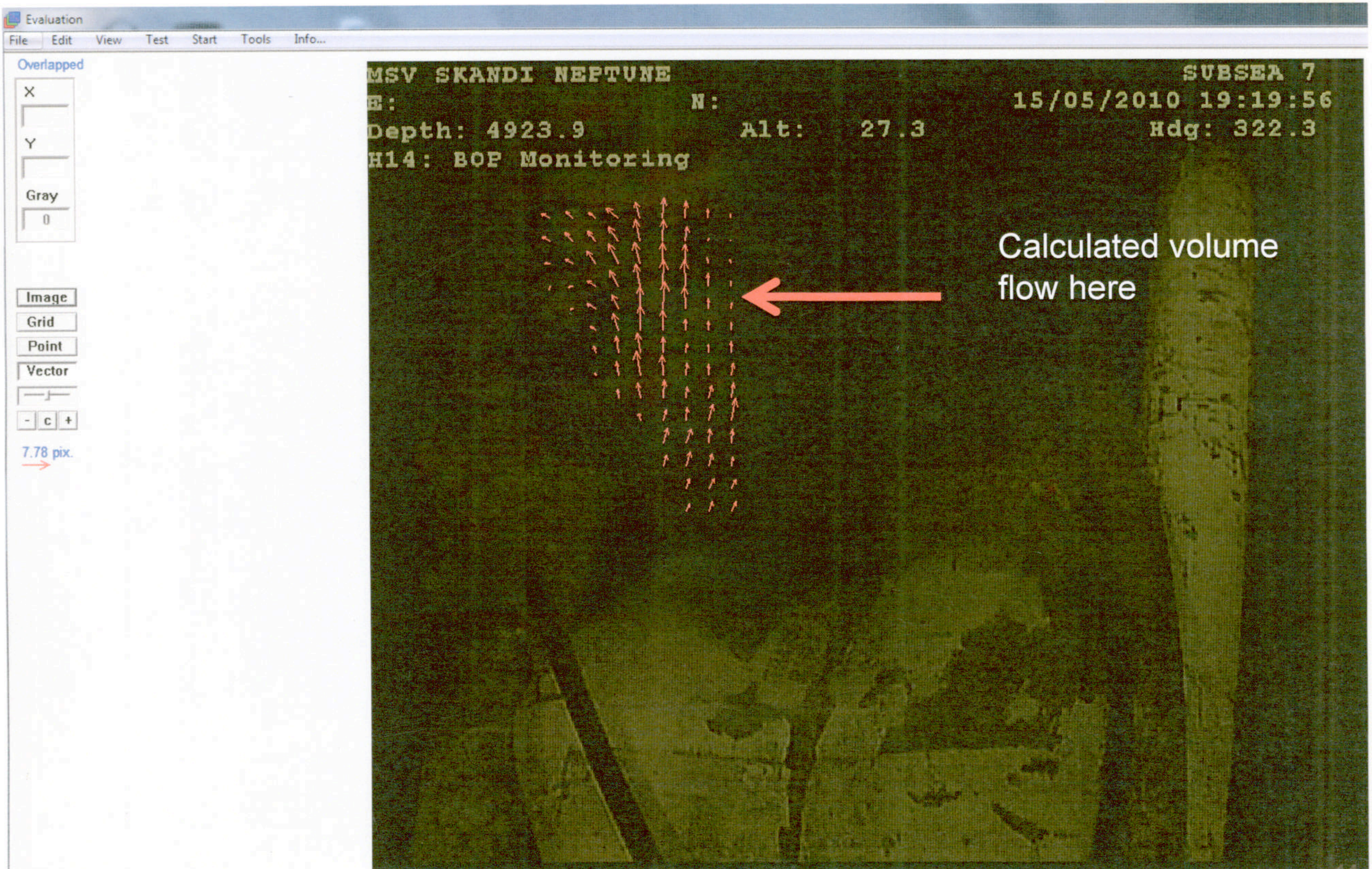
H14 BOP Plume May 15 1920-1945

- Used ensemble of 25 images
- Only measured flow from one source
  - Left source too difficult to measure
  - Seems of comparable flow
- Average velocity: 6.95 in/s
- Diameter at that location: 7.61 in
- Volume flow: 2814 bbl/day

Overlapped image to show jet boundaries

PURDUE UNIVERSITY Discovery Park

Vector field



How can these results be improved?

- Calculations are total flux (gas + oil)
- Better values for
  - Gas/Oil Ratio
    - Independently verified
  - Riser cross section area
    - Need photo, shape matters
- Better quality, longer videos
  - Existing videos are
    - low quality
    - compressed
    - screen captures

Appendix 7

Dr. Ira Leifer, University of California, Santa Barbara
As a participant to two efforts to estimate oil emissions, one as part of the Technical Flow Rate Task Force, and one as the chief mission coordinating scientist on an airborne remote sensing effort in response to the Deepwater Oil Spill, cooperatively using NASA, NOAA, and USGS resources.

Both studies only could address a limited fraction of the oil; one subsea related analysis of data available from BP, 2, remote sensing data from above. Neither can conclusively establish a reasonable scientific determination for an upper bound. Further. there is a critical lack of independent validation by ground reference measurements, which I urge be prioritized.

Additional study that would integrate these two studies with additional research hopefully will be able to establish an upper bound and resolve the total amount of oil spilled. However, the two studies I have been on do demonstrate the evidence of oil and provide for a reasonable scientific estimate of a minimum amount of oil spilled.

I agree with the report statement that actual emissions could be higher, potentially significantly; by no means should this estimate be seen as a evaluation of the total oil spilled, but only a floor.

At the seabed, insufficient data has been provided by BP to the TFRT to date. When the data was provided it was provided in an untimely manner and the data that was provided was of unacceptably low quality. Further, BP selected a few minutes of data from the many hours of data at their disposal. It was never explained to the TFRT team why this data was selected.

Extrapolating from such a not-independently selected and tiny data set has a high likelihood of leading to incorrect conclusions.

Similarly, the remote sensing data set is incomplete with regards to estimating total oil at the sea surface as it only provides information on the portion of the ocean covered by the NASA AVIRIS (airborne visual infrared imaging Spectrometer) sensor during the AVIRIS flights. Similarly, the analysis only provides information on the thick oil portion of the slick. AVIRIS's data provides a snapshot map for inventorying certain thick oils at the surface, but not all of the crude oils that might have been emitted. Thus, it provides an incomplete dataset for deriving a total survey of the emitted oil.

Accurate assessment of a flow rate must consider oil unobserved by these techniques, including evaporative losses, the effect of dispersants, and natural dispersion. In addition, remote sensing cannot detect submerged oil, which initial estimates, not addressed in the remote sensing study, suggest could be substantial.

My own estimation based on the remote sensing data and a decade of experience in studying oil's behavior in the ocean, including numerous peer-reviewed publications, suggests that total emissions are significantly larger than the conservative lower bound estimate.

Similarly, analysis by comparison with field data from shallow bubble plumes with similar

characteristics supports a higher flow rate than the conservative lower bound presented in this report.

There is a critical lack of independent validation by ground reference measurements, which I urge be prioritized. Specifically, the flow should be measured directly, should recent efforts fail. Further, there is a need for a field validation experiment for the remote sensing data. Independent validation based on direct measurements would greatly increase the confidence in any flow estimates and greatly reduce the uncertainty.

Specific comments follow:

As has been noted, the video is of very poor quality because that is what BP provided. Low quality video can introduce errors and biases into ICV (Imaging Correlation Velocimetry). Thus, high quality video is key to providing the most accurate estimate.

My recommended approach:

Specifically, use ICV to get a mean flow from a statistically significant number of measurements.

Make reasonable assumptions on what the flow profile across the plume is.

Use the variability from a proxy (or the flow if we are allowed time) to provide uncertainty bars on the flow based on a statistical (i.e., empirical) approach to assign confidence limits on these error bars.

Leave overly sophisticated tools, like CFD for a NSF proposal, which are unlikely to reproduce the unique deep sea gas characteristics correctly absent largely absent and recommend that such research be supported for future spill preparedness. We can always make a range of uncertainty assumptions on the difference between image structure apparent motion and actual fluid motions.

I also recommend that a field experiment be fast-tracked. What we learn from the ICV studies will aid in the design of a verification study. Such a study is critical because the behavior of plumes in laboratory studies at close to atmospheric pressures is highly divergent from behavior at depth, as has been demonstrated in deep-sea field studies.

Key observations about the video used in the

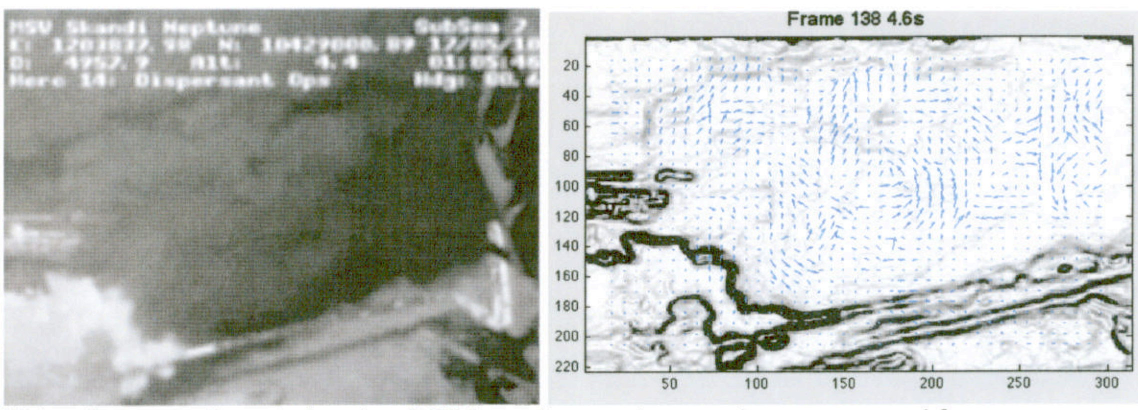
1. There are one or more ROV operations in the area, which are creating currents. These should be known and noted for the discussion, but in some portions of the data analysis do not cause problems in the velocity analysis. Evidence for secondary ROV activity are two large chunks of what could be hydrate sediment clumps are observed falling at frame 6119 of 7500, through the scene, confirmed in the unprocessed video at 3:59:14. Their trajectory is such that they must have come from a nearby ROV above - we had similar problems this summer at MC118 with hydrates forming on the ROV bottom after sitting at the seabed in a bubble-oil plume area. Also, at some point (2:46:18) another ROV turns on its light, changing the scene illumination.

Understanding the intermittency is critical, because it is very variable. Longtime series

need to be analyzed. Variability in the plume morphology due to turbulence structures as revealed by the scene illumination are indirectly related to the flux assuming no illumination changes from a moving ROV. In that sense, a quick look at the relative grey level suggests that analysis on the timescales of the higher frequency (< 10 s) oscillations is independent of the scene illumination change. This independence could be confirmed by creating a spectragram as used in acoustic analysis. However, the long-term oscillatory pattern easily could be biased, and furthermore, 1.5 cycles does not make for good characterization of a ~100 - 200 s pattern (I would recommend a spectral approximation approach for the long period components).

I interpret this as indicating greater uncertainty.

I improved contrast through running a Cany-Derich type edge detection filter on the image sequence (which I also loaded into video editing software for easy viewing, such software allows easy scanning hours of video). From the processed image sequence, it is clear that the plume consists of three separate bubble-oil plumes. Each has its own oil to gas ratio, flow velocities, and thus follows distinctly different trajectories.



Video frame grab and showing DPIV result superimposed on processed frame.

These three plumes could arise from:

1. Structures and resultant fractionation in the pipe,

2. Fractionation in the horizontal jet. The trajectories and distinctly different shading (unfiltered) clearly indicate that the gassiest has the most vertical trajectory.

These three distinct plumes are more readily apparent during the gassy phase.

During the oily phase, at one point, the velocity vectors "stop" for ten or so frames. Close inspection reveals that at this time the plume is almost purely three-dimensional. The plume is expanding towards the view angle. Thus, velocities during this phase cannot assume a two dimensional plume, which means flow is non-negligibly underestimated.

During the first oily phase, several more hydrate-sediment (?) clumps drop through the field of view, some distance in front of the actual plume. These correspond to a time period when the plume is at its weakest (oiliest), as a result, the data analysis I am seeing coming through now shows turbulence billows being blown into the plume from an external source. As a result, flow measurements during the oily phase are highly

contaminated and must be closely evaluated. Because introduction of additional turbulence energy would have the effect of lowering the flow rate, this would bias flow estimates lower. Analysis of scene velocities with altitude above the plume origin would allow a decent estimation of the effect. Analysis of better data is key.

In the far stronger gassy phase of the plume, ROV flow disturbance appears to be negligible.

One key factor that needs consideration in terms of estimating the oil to gas ratio is that it is likely that the gas phase is not in hydrostatic equilibrium where it exits the leaks. This is unsurprising given that we are observing classic, fully-developed slug flow in this pipe-driven flow (a common phenomena in marine seepage), with the oil slug providing resistance against gas flow.