NATIONAL ENERGY TECHNOLOGY LABORATORY

Work For Others (WFO)

Development of a ROV Deployed Video Analysis Tool for Rapid Measurement of Submerged Oil/Gas Leaks

September 17, 2013

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Revision Log

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0	September 17, 2013	Frank Shaffer	First Draft

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Executive Summary

With expanded deep sea drilling in the Gulf of Mexico and possible deep sea drilling in the Arctic, having a technology available to quickly and accurately measure the discharge rate from a submerged oil/gas leak jet is imperative. One of the first responses to a submerged oil/gas leak will be to send a remotely operated vehicle (ROV) down to view the leak with video. An ROV deployed video analysis tool is thus proposed for rapidly measuring the discharge rate from a submerged oil or gas leak. Video from an ROV can be used to measure the velocity of visible features (turbulent eddies, vortices, entrained particles) at the boundary of an opaque oil leak jet. Using classical theory of turbulent jets, the velocity of visible features can be used to estimate the discharge rate of an oil leak jet. This approach was developed by two of the principle investigators (PIs) of this proposal, Savas and Shaffer, while serving as members of the Flow Rate Technical Group's (FRTG's) Plume Team during the Deepwater Horizon (DWH) oil leak [FRTG, 2010]. Significantly, this technique provided the first accurate, official estimates of the oil leak rate [McNutt et al., 2011]. With funding from DOE, Savas and Shaffer are now starting to test this technique on submerged gas leak jets.

Although this technique has been shown to produce accurate estimates of oil leak rates, Savas and Shaffer have identified several obstacles that must be overcome before this technology can be accepted and widely implemented. One of the main obstacles is the absence of video analysis software to automatically measure the velocity of visible features. During their work on the Plume Team, Savas and Shaffer discovered that the automated video analysis software being used by the Plume Team, called Particle Image Velocimetry (PIV), was producing erroneously low velocities that resulted in gross underestimates of the oil leak rate [McNutt et al., 2010]. Savas and Shaffer had to resort to laborious manual tracking of visible features in ROV video. Manual analysis, i.e., having a human track visible features by hand, is not practical for widespread implementation of this technology. The experimental work of Savas in 2010 [Savas, 2012] on dye colored water jets provides further evidence that using existing PIV software can produce erroneous results.

Another obstacle is a lack of understanding of the visible coherent features and how they are related to the internal velocity profiles of an opaque oil leak jet. Visible coherent features, e.g., turbulent eddies and vortices, have a wide range of sizes and velocities at the boundary of submerged turbulent jets [Schlichting, 2004; Lee and Chu, 2003]. In their work on the FRTG Plume Team, Savas and Shaffer selected only the largest, fastest visible features, but it is not clear why this produced accurate estimates of the oil leak rate. More experimental data is needed to define how visible features relate to the internal velocity profiles of a submerged oil leak jet.

Subsequent research by Savas and Shaffer also indicates that higher frame rates, in the range of 100-500 per second, might be required. The cameras on the ROV's used to view the DWH oil leak jets had a frame rate of only 25 per second. The low frame rate may have played a role in the failure of automated PIV software used by the FRTG Plume Team. A systematic study of the effect of frame rate on ICV results has not been performed, but it will be done as part of this project.

We propose an intensive one-year project to overcome these obstacles and produce a proven technology that is ready to be turned over to responders for widespread implementation. To prove this technology, we propose to use the OHMSETT facility to create a submerged oil leak jet with characteristics similar to a major deep sea oil leak such as the DWH. The oil leak jet will be dyed for flow visualization and recorded with high-speed, high-resolution video. Standard high definition video will also record the oil leak jet from several perspectives. Creating a large, well controlled oil jet at OHMSETT will also provide a rare opportunity for other organizations to study other characteristics of a realistically large oil plume, such as breakup of the oil into droplets or the effect of dispersants.

To develop a clear understanding of the coherent visible structures and how they relate to the internal velocity profiles of an oil leak jet, we propose small-scale experiments and complimentary computer simulations. The small-scale experiments will be performed at the University of California (U.C.) Berkeley to produce high-resolution velocity maps of the coherent features and internal velocities of a submerged oil jet. A small-scale oil jet will be created in a 4' x 4' x 8' transparent glass water tank at U.C. Berkeley. The oil jet will be mapped with a PIV, a laser imaging technique that requires use of a high-power (Class IV) laser that cannot be safely used at OHMSETT.

NETL will perform computer simulations of the oil jet experiments at Berkeley and OHMSETT using computational fluid dynamics (CFD). NETL has extensive experience with modeling multiphase flows and was called on during the DWH crisis to simulate the DWH oil leak jets [FRTG, 2010]. As a DOE national lab, NETL has one of the fastest supercomputers (24,192 parallel CPU cores producing over 500 TFLOPS) in the world. NETL will generate CFD simulations of the internal velocity profiles and visible features of the oil leak jets created at Berkeley and OHMSETT. The exact size and velocity of visible features will be known in the CFD simulations. Thus, CFD simulations will not only give insight into the nature of visible features, but will also produce a known test case with which to test automated video analysis software.

To address the need for automated video analysis software, Shaffer and Savas – who both have extensive experience over the past three decades in developing automated video analysis software for measuring fluid flow rates [Savas 1986, 2000, 2012; Shaffer, 1988, 1994, 2013] – will work with a full-time post doctoral researcher to develop a video analysis software package. This team will modify Savas's image correlation velocimetry (ICV) flow measurement software called Advanced Lagrangian Parcel Tracking (ALPT). The ICV ALPT software was designed to measure the velocity of visible objects entrained in a fluid flow field. The new version of the ICV software will be documented and made available to the public.

The OHMSETT Test Director, Dave DeVitis, is also a PI on this project. Because DeVitis led the design of much of the oil injection and cleanup equipment at OHMSETT, his participation will ensure successful oil jet experiments at OHMSETT. NETL, BSEE and OHMSETT will work together to invite other organizations to make simultaneous measurements of the submerged oil jet and subsequent oil slick.

The deliverables of this project will be documentation and software that can be used by responders to measure the discharge rate from a submerged oil leak jet. Documented instructions will be delivered that describe how to use this technique, including the video analysis software and specifications for the type of camera equipment required. We will work with responding organizations, e.g., NOAA and the U.S. Coast Guard, to further develop protocols for application of this technology.

Project Overview

This approach uses video from a Remotely Operated Vehicle (ROV) to measure the velocity of visible structures (e.g., turbulent eddies, vortices, hydrates or wax particles) on the boundary of an oil/gas leak jet. Figure 1 shows the flow of visible structures on the DWH oil leak jet through three consecutive video frames.

The proposed ROV video tool will consist of: (1) a moderate speed (likely in the range of 100 to 500 frames/sec) camera mounted on a ROV, (2) a means to transfer video data to computers at the surface, (3) an automated video analysis tool to measure the velocity of visible structures on the boundary of a leak jet, and (4) instructions on how to find the oil discharge rate using the velocity of visible features.

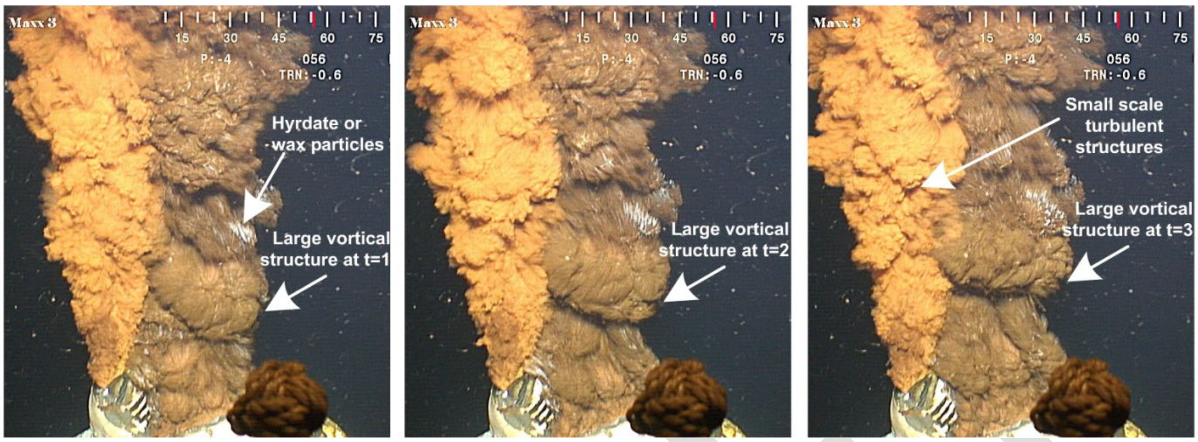


Figure 1. Examples of visible structures propagating in the flow direction on the Deepwater Horizon oil leak jet.

In early June 2010, almost two months before the discharge rate of the Deepwater Horizon Macondo well was measured in the well capping system, Savas used this approach to produce an official estimate of 46,000 barrels per day (bpd) and Shaffer used this approach to produce an official estimate of 55,000 to 61,000 bpd [FRTG, 2010]. The U.S. government's final estimate on August 2, 2010, was 53,000 to 62,000 bpd. Shaffer's estimate was the first accurate, official estimate of the DWH leak rate [see Fig. 4 of McNutt, 2011].

This approach is relatively inexpensive and easy to apply. If it is shown that standard camera frame rates (30 to 60 per second) are adequate for this technique, existing cameras on ROVs can be used, so there will be no cost for additional hardware. If it is found that higher frame rates in the range of 100 to 500 per second are required, a moderate speed camera will need to be added to a standard ROV. Consumer level HD cameras capable of 500 frames/second are available for costs in the range of $1000-$5000. Professional level cameras capable of 500 frames/second are available for costs in the range of $5000-$10000. The low cost of this technology will allow widespread implementation. Other technologies for measuring submerged oil leak rates, like sonar, are much more expensive and usually require a specialized ROV. This ROV video technology requires only the addition of a moderate speed camera to any standard ROV and software to analyze the video.

Theory of Submerged Turbulent Jets

The theory of submerged turbulent jets is well established. Prandtl [1925] and others developed the theoretical foundation in the 1910's and 1920's. With recent advances in CFD, the behavior of submerged turbulent jets can be simulated [Ball, 2012].

Figure 2 illustrates the velocity profiles of a submerged turbulent jet emitting into an infinite body of fluid at rest. The edges of the jet shear against the surrounding fluid causing the formation of a turbulent shear mixing layer. The shearing action also causes the jet to expand as the surrounding fluid is entrained into the jet. The radial profile of streamwise velocity begins as a flat profile (nearly constant velocity) at the jet exit, then gradually transform into a Gaussian profile. Because submerged turbulent jets are self-similar, all submerged turbulent jets, regardless of the jet fluid, have the same divergence angle, usually around 24 degrees (Lee, 2003). The statistical jet boundary is a point on the radial profile of mean streamwise velocity where the value decreases below a predefined level. The statistical jet boundary lines converge at a focal point at a distance of $2.5D_{jet}$ upstream of the jet exit, referred to as the virtual origin.

The velocity at the statistical boundary, u_{sb}, is not the same as the velocity of visible features, u_{vf}, i.e., $u_{vf} \neq u_{sb}$. Therefore, existing data cannot be used to relate the velocity of visible features to the internal velocity profiles of an opaque oil jet.

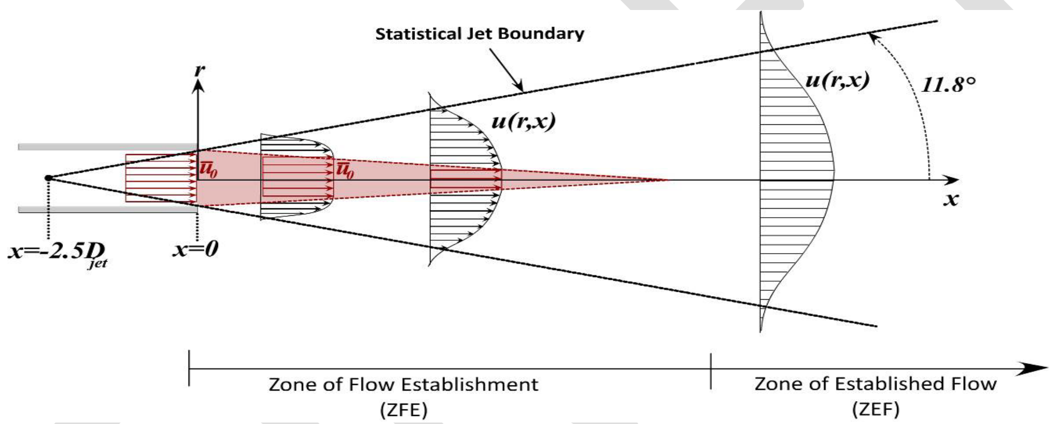


Figure 2. Velocity profiles and regions of a submerged turbulent jet.

The distance from the jet exit in which the jet has a constant velocity core of $\overline{u}_0$ (the diverging area shaded in red) is called the zone of flow establishment (ZFE) (also called the developing zone, potential core, or near field). For a submerged jet exiting from a round exit, the ZFE is 6.2 exit diameters long [Lee & Chu, 2003]. The boundaries of the constant velocity core are formed by points where the velocity decreases infinitesimally below $\overline{u}_0$.

Downstream of the ZFE is the zone of established flow (ZEF), where radial profiles of mean streamwise velocity are Gaussian and self-similar. Self-similar means that at any distance, *x*, all data for mean velocity fall on the same radial profile when plotted in the non-dimensional form of $u(r)/u_c$ and r/R_{jet}, where u_c is the centerline velocity at x and R_{jet} is the radius of the jet at x.

Lee and Chu derive equations for the radial profiles of mean velocity and concentration in a submerged turbulent jet [2003]. In the ZFE, inside the constant velocity core, for $r < R_{core}(x)$, where $R_{core}(x)$ is the half width of the constant velocity core, the velocity and concentration (fraction of fluid at any point that is jet fluid) are given by

$$u(x,r) = u_0 \qquad\qquad c(x,r) = c_0 \tag{1.0}$$

In the ZFE, outside the constant velocity core, where $r > R_{core}$, the velocity and concentration are given by:

$$u = u_0 \exp\left[-\frac{(r - R_{core}(x))^2}{b^2}\right] \qquad\qquad c = c_0 \exp\left[-\frac{(r - R_{core}(x))^2}{\lambda^2 b^2}\right] \tag{2.0}$$

where b is the half width of the jet from the centerline to the statistical jet boundary and λ is a turbulent diffusion coefficient. In the ZEF, the velocity profile is given by:

$$u = u(x,0)\exp\left[-\frac{r^2}{b^2}\right] \qquad\qquad c = c(x,0)\exp\left[-\frac{r^2}{\lambda^2 b^2}\right] \tag{3.0}$$

The half width of the jet is given by $b = \beta x$, where β is the slope of the statistical jet boundary. The experimental work of Albertson (1950) and Wygnanski and Fiedler (1969) found that $\beta = 0.114$ for a submerged turbulent jet emitting from a round orifice. The diffusion coefficient, λ, is equal to the ratio of the divergence angle of the statistical concentration boundary to the divergence angle of the statistical jet boundary. Experimental work of Papanicolaou and List (1988) found that $\lambda = 1.2$ for a submerged turbulent jet, indicating that the concentration half width is larger than the velocity half width.

Measurement of the Discharge Rate from a Submerged Oil Jet

The following equation was used by members of the Plume Team during the DWH crisis to calculate the oil discharge rate:

$$\dot{Q}_{oil} = \overline{u}(x) A_{jet}(x)\left[1 - X_{GOR}\right]E(x) \tag{4.0}$$

where

$\overline{u}(x)$ is the average jet velocity at a downstream distance, x, from the jet exit.

$A_{jet}(x)$ is the cross sectional area of the jet at a distance downstream from the jet exit

X_{GOR} is the volume fraction of methane gas dissolved in the oil. Near the jet exit, methane was dissolved in the oil. Downstream the methane was liberated from the oil.

$E(x)$ is the proportion of sea water entrained into the jet at any distance x.

The jet cross sectional area, $A_{jet}(x)$, can be found by measuring the jet diameter from the ROV video at the distance *x* where the visible jet boundary velocity was measured. The gas-to-oil ratio, X_{GOR}, was found by sampling the oil with ROV probes and bringing it to the surface for analysis. The entrainment parameter, *E(x)*, can be found by measuring the expansion of the jet, or by using theory such as that of Lee and Chu [2003] as described above in Equations 1-3.

The Plume Team encountered several challenges in applying this approach. The first challenge was how to measure the velocity of visible features on the boundary of the immiscible oil leak jets. Six members of the Plume Team began by using automated video analysis software that was developed for PIV to automatically measure the velocity of visible features. Three of the team members (Leifer, Savaş and Shaffer) concluded that the PIV software was producing erroneously low values of velocity that led to gross underestimates of the oil discharge rate [FRTG 2010; McNutt 2011]. They resorted to manual tracking of larger, faster visible features by hand.

The next challenge was to determine the relationship between the velocity of visible features, u_{vf}, and the mean velocity of the jet, $\overline{u}(x)$. During the work of the Plume Team and during subsequent studies by Savas and Shaffer, literature searches found no previous research to relate u_{vf} to $\overline{u}(x)$. Therefore, each member of the Plume Team had to make an educated guess for the relationship between u_{vf} and $\overline{u}(x)$ [Shaffer et al., 2013].

The final challenge was to estimate the amount of water entrained into the oil jet, *E(x)*. The amount of entrainment can be calculated using the expansion of the jet or the theory of Lee & Chu [2003] described in equations 1-3. However, the theory of Lee and Chu has not been proven for an immiscible jet, and very little data is available for immiscible jets submerged in water.

The proposed oil jet experiments at Berkeley and OHMSETT and NETL CFD simulations will allow us to overcome the abovementioned challenges.

Research of Savas and Shaffer to Develop this ROV Video Approach

Savas and Shaffer have continued to develop this approach after their work on the Plume Team by using dye colored water jets in the Berkeley Tow Tank facility [Savas, 2012, Shaffer et al., 2013]. In October of 2010, Savas conducted experiments to simulate a large, submerged oil leak using a dye colored water jet with an 8" exit diameter at flow rates up to 5 gallons/sec in the U.C. Berkeley Tow Tank Facility. Savas tested several automated video analysis techniques on his video of dyed water jets [Savas, 2012].

In 2012, Shaffer joined Savas at the Berkeley facility for more extensive experiments. The flow rate was increased to 11 gallons/second, thereby matching the Reynolds numbers of the DWH oil leak jets; the dye-colored jet was recorded with high definition, high-speed video, and jet velocities were mapped with Laser Doppler Anemometry (LDA), a highly accurate velocity measurement tool. The LDA data served as a reference with which to evaluate the accuracy of ICV software.

Shaffer and Savas applied Image Correlation Velocimetry (ICV) software to the high-speed video to measure the velocity of visible dyed features. They found that automated ICV software can measure the mean velocities of dyed visible features that are in good agreement with LDA data. Figure 3 shows a comparison of mean velocities measured with ICV and LDA. Figure 4 shows an overlay of velocity vectors measured with ICV on an image of a dye colored water jet.

Although ICV was able to measure velocities in good agreement with LDA, ICV results were found to be sensitive to the size of template and interrogation regions, as well as preprocessing steps to enhance the video. The effect of sizes of template/interrogation regions and preprocessing steps will be investigated in the proposed project.

Savas recently published a paper in *Experiments in Fluids* [Savas, 2012] in which he described analysis of dye colored water jets using several different automated video analysis approaches, including ICV/PIV, ALPT, and Lagrangian edge tracking. Savas and Shaffer have submitted a 25-page paper describing this work to the *Journal of the Society of Petroleum Engineers* [Shaffer et al., 2013].

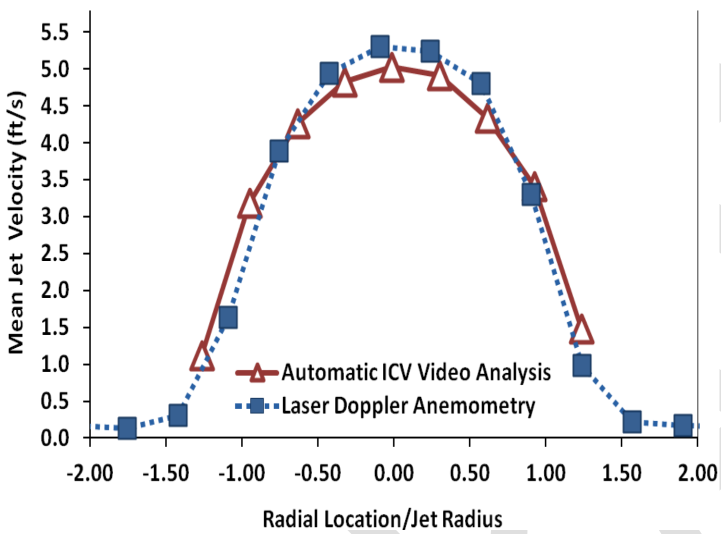


Figure 3. Comparison of automatic ICV data with LDA data for the radial profile of mean streamwise jet velocity at four jet diameters downstream of jet exit. Measurements by Shaffer and Savas [Shaffer et al., 2013]

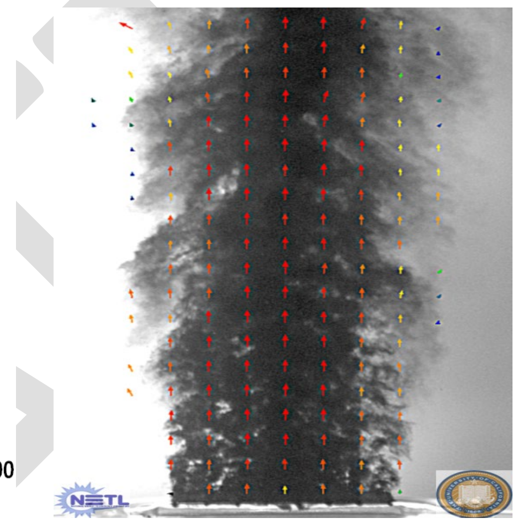


Figure 4. Dye colored submerged water jet with automated ICV analysis of jet velocity field. Measurements by Shaffer and Savas [Shaffer et al., 2013]

With funding through DOE's EPAct program, Savas and Shaffer are scheduled to start testing this technology on submerged gas leaks in Berkeley's Tow Tank facility. Four weeks of tests with submerged gas leaks are scheduled to start in July of 2013. We believe it is likely that this technology will also be able to measure discharge rates from submerged natural gas leaks.

Risk Management

Description

Project risk events are defined as uncertain future events that, if realized, negatively or positively impact the success of the project. Identified project risks should be assessed on a regular basis to measure the probability of occurrence and consequence or impact to the project. Risks that occur early in the project usually have a lower impact to project success since there is time available for recovery. Risks that occur later in the project have more of a negative impact to the project success depending upon planned mitigation strategies. Periodic assessments serve two main purposes: (1) keeping the project team aware of risk triggers leading to potential project risks, and (2) providing a mechanism for classifying identified risks at key decision points along the critical path. Risk management is also necessary to assure that negative risk that would impede or preclude the timely achievement of established goals and targets are identified and reasonably mitigated, and positive risks are considered and possibly pursued. Risk probabilities commonly diminish or retire as the project progresses.

This section presents a risk management strategy for the project. Project risks will be identified and monitored throughout the project life cycle, reviewed with the key technical and managerial staff during status reviews on a quarterly basis, and mitigated to the extent possible using a variety of means. The Risk Register is provided in Appendix A and reflects current risks and their levels. The Risk Register will be updated quarterly in the Quarterly Progress Report. Risks will not be updated in the PMP unless an official revision is made.

Project Risk Assessments

A semi-quantitative scoring methodology was used for application of the Risk Register for the project based on a 5 by 5 risk ratings matrix illustrated in Table 1. Both the likelihood (probability) and potential impact (consequence) of the risk event were considered, resulting in an overall risk rating.

In the Risk Register, the following ranking was used for the probability of event occurrence:
(1) Very High – >90%, (2) High – 75 to 90%, (3) Moderate – 26 to 74%, (4) Low – 10 to 25%, and (5) Very Low – <10%. The following ranking was used for the consequence of event occurrence:
(1) Negligible, (2) Marginal, (3) Significant, (4) Critical, and (5) Crisis. These probabilities and consequences result in the risk ratings matrix used to determine the risk rating.

Table 1: Risk Ratings Matrix

			Consequence				
			Negligible	**Marginal**	**Significant**	**Critical**	**Crisis**
Probability	**Very High**	>90%	Low	Moderate	High	High	High
	High	75 to 90%	Low	Moderate	Moderate	High	High
	Moderate	26 to 74%	Low	Low	Moderate	Moderate	High
	Low	10 to 25%	Low	Low	Low	Moderate	Moderate
	Very Low	<10%	Low	Low	Low	Low	Moderate

(Source: Updated Guidance for Recovery Act Risk Assessment and the DOE Risk Management Guide, DOE G 413.3-7, 9-16-08)

Risk Register

In accordance to SCC Procedure SCC-PMP-IV-1, Project Risk, and NETL Project Management Guidelines, Extramural Research, Development, and Demonstration, risks were identified and placed in a Risk Register. The Risk Register for this project is updated each quarter in the Quarterly Progress Report. The Risk Register was used to identify risks and mitigating measures for the project. This initial baseline of risks was in line with industry standard practices and NETL recommendations.

- Financial
- Cost/Schedule
- Technical/Scope
- Management, Planning, and Oversight
- Environmental, Safety, and Health (ES&H)
- External Influences
- Other

The Technical Monitor (TMo) will act as an accountable official, reassessing project risk on a quarterly basis derived from the Office of Risk Management's requirements and providing the results of the reassessments to the SCC.

The project's technical and managerial teams will review the Risk Register on a quarterly basis to assess existing risks. The teams will:

- Consider whether to update each risk's probability, consequence, and resulting risk rating.
- Determine whether new risks should be added to the register.
- Examine whether previously identified risks can be retired from the register.
- Ensure that each identified risk is effectively updated, and the status is reported.
- Determine new ideas to mitigate the previously identified risks based on new discoveries.
- Decide if any risk probabilities become eminent by following the extent to which they impact the baseline duration estimate for each scheduled activity.
- Identify any improvements that can be made to the existing risk management plan.
- Update the management actions where appropriate.
- Evaluate the current association of risk to a particular entity or entities that are impacted by the risk and update appropriately.
- Provide the updated Risk Register to the SCC Technology Manager (TM).

Milestone Log

The major milestones for this project are presented in Table 2, in the GAANT chart in Figure 17, and Appendix B. The milestones and GAANT chart are taken from the NETL proposal that BSEE funded for this project. In Appendix B, identifiers are placed on the Gantt chart. These milestones will be placed in M1 and will be tracked and reported on in quarterly technical progress reports.

The schedule and milestones for the proposed project are shown in the Figure 17. The time scale represents months from project initiation. Because the data produced in the Berkeley oil jet experiments and the computer CFD simulations will be used to test the automated video analysis software, the Berkeley experiments and computer simulations will be completed in the first three to four months of the project. Development of the automated video analysis software will also start at the initiation of this project. The oil jet tests at OHMSETT will be done later in the project, in the April-May time frame, depending on availability of the OHMSETT facility.

Table 2: Support Milestone Log

Milestone Identifier	Title	Planned Date	Verification Method
Task 0.0 Project Management			
M1.A	Submit FY14 Annual Report	11/29/2014	E-mail transmittal to ORD Associate Deputy Director for Research (ADDR&D)
M1.B	Submit Final Report	2/15/2015	E-mail transmittal to ORD Associate Deputy Director for Research
Task 1.0 OHMSETT Experiments			
M1.C	Task 1.1: Design & Construction of Dye Injection System	02/31/2014	Shakedown tests at OHMSETT
M1.D	Task 1.2: Design & Construction of Camera Mounting/Translation System	03/31/2014	Shakedown tests at OHMSETT
	Task 1.3: Design & Construction of Oil Jet Injection System	4/31/2014	Shakedown tests at OHMSETT
	Task 1.4: Large oil leak jet experiments at OHMSETT	5/31/2014	Tests at OHMSETT
Task 2.0 Berkeley Oil Jet Experiments			
M1.E	Task 2.1. Shakedown testing in Berkeley small water tank	02/30/2014	Shakedown testing
M1.F	Task 2.2 Oil jet imaging tests at UC Berkeley	04/30/2014	Data produced from Berkeley experiments
Task 3.0 Task III: Software Development & Documentation			

Milestone Identifier	Title	Planned Date	Verification Method
M1.G	Task 3.1: Evaluate software using data from Berkeley experiments	06/30/2014	Testing results
M1.H	Task 3.2: Evaluate software using CFD Simulations	07/30/2014	Testing results
M1.I	Task 3.3: Evaluate software using OHMSETT data	08/30/2014	Testing results
M1.J	Task 3.4: Optimization of software for minimum CPU time	09/30/2014	Testing results
M1.K	Task 3.5: Documentation for leak measurement procedures and application of software	12/30/2014	Documentation
Task 4.0 Computer CFD Simulations of Submerged Oil Jets			
M1.L	Task 3.1: Evaluate software using data from Berkeley experiments	06/30/2014	Testing results
M1.M	Task 3.2: Evaluate software using CFD Simulations	07/30/2014	Testing results
M1.N	Task 4.1: Computer Simulations of Berkeley Oil Jet Experiments	02/30/2014	Data and video simulation
M1.J	Task 4.2: Computer Simulations of OHMSETT Oil Jet Experiments	06/30/2014	Testing results
Task 5.0 Reports			
M1.K	Quarterly Report	1/10/2014	Quarterly Report
M1.M	Quarterly Report	4/10/2014	Quarterly Report
M1.N	Quarterly Report	7/10/2014	Quarterly Report
M1.O	Quarterly Report	10/10/2014	Quarterly Report
M1.P	Final Report	1/10/2014	Final Report

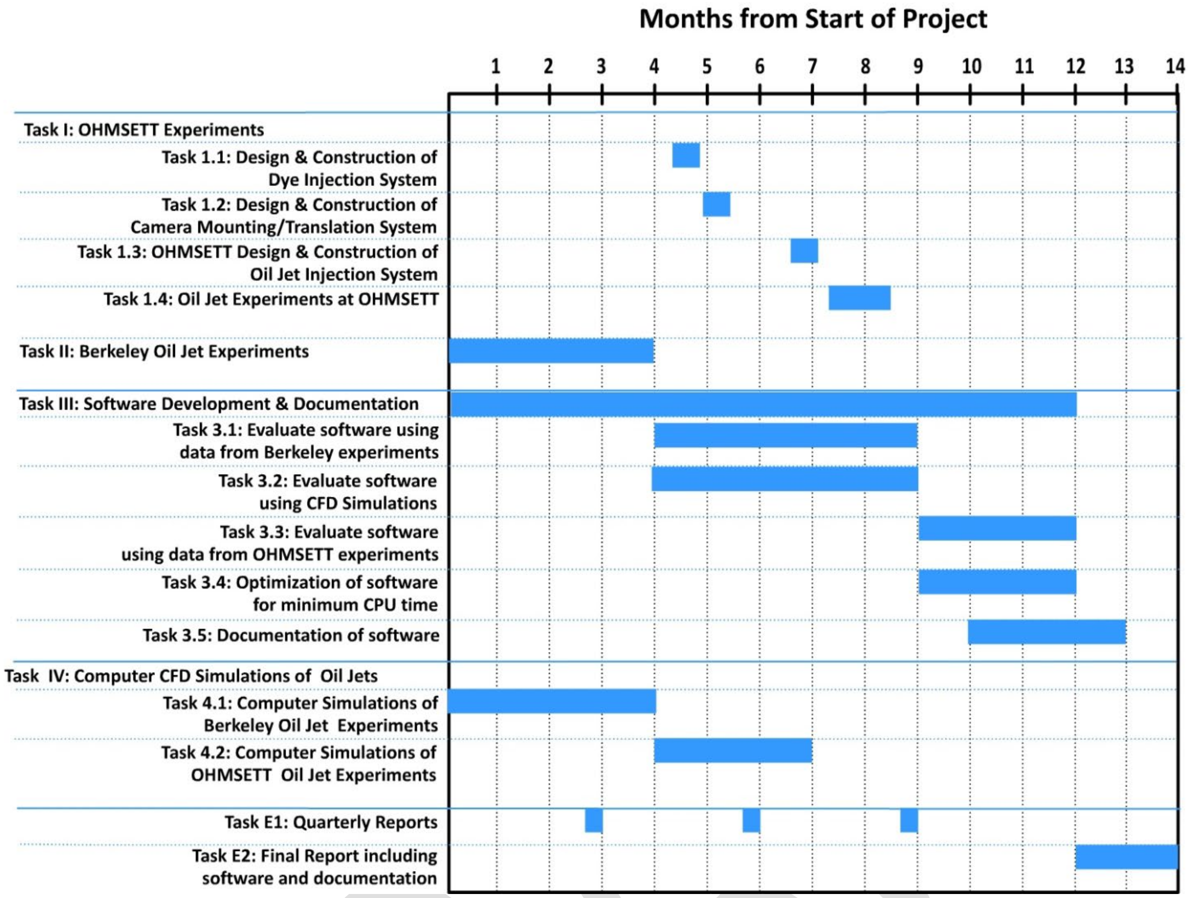


Figure 5. GAANT chart showing tasks and schedules.

Funding and Costing Profile

The project's task structure with involved organizations and approximate budgets for each task is shown in Table 3. A high-level budget table is provided in Appendix C.

Table 3: Task Structure, Involved Organizations, and Budget for FWP Number:

The overall contract is now for $709,800.

$249,038 to UCB (in green below)
NETL breakdown as follows:

Federal Labor	$	109,262.19
Fringes (federal only)	$	32,778.66
Contract Labor - URS	$	-
Contract Labor - RUA	$	-
Contract Labor - ORISE	$	-
Contract Labor - Other	$	-
Subawards and consultants	$	249,038.00
Total Contractual	$	249,038.00
Capital Equipment	$	17,697.00
Materials & Supplies	$	-
Travel	$	16,932.68
Other Direct Costs	$	-
Total direct costs	$	425,708.53
NETL Indirect Cost	$	148,432.69
ORD Indirect Costs	$	114,941.30
DOE Indirect Costs	$	-
DOE Federal Admin Fee (Non-DOE proposals)	$	20,672.48
Total Indirect costs	$	284,046.47
TOTAL	**$**	**709,755.00**

Project Timeline

The project timeline is included above in the GAANT chart in Figure 17. This timeline shows activities (i.e., tasks and subtasks) in accordance with the work breakdown structure (WBS). The schedule and milestones completion status will be updated in the quarterly progress reports.

Success Criteria and Decision Points

Objectives

The main deliverables will be quarterly, draft final and final reports, automated video analysis software, documentation on use of the software, and documentation describing the measurement of discharge rates from submerged oil leak jets using ROV video. The reports will be provided as requested in the technology assessment and research (T A&R) guidelines in both MS Word and PowerPoint versions suitable for BSEE hardware and software. Any results prepared for presentation or publication will also be sent to BSEE prior to initial submission to the conference or journal. The reports will include the following:

a) A summary of the preceding work and overall progress made against the schedule
b) Experimental data from the Berkeley and OHMSETT oil jet experiments
c) Computer CFD simulations of oil jets in the OHMSETT and Berkeley experiments
d) Analysis of the experimental results, including comparison with computer CFD simulations
e) Analysis of the performance of automated video analysis software in measuring the flow rate of the OHMSETT and Berkeley oil jet experiments
f) Automated video analysis software
g) Documentation for use of automated video analysis software
h) Documentation explaining the application of this technology to measure discharge rates from submerged oil leak jets.

Success Criteria and Decision Points

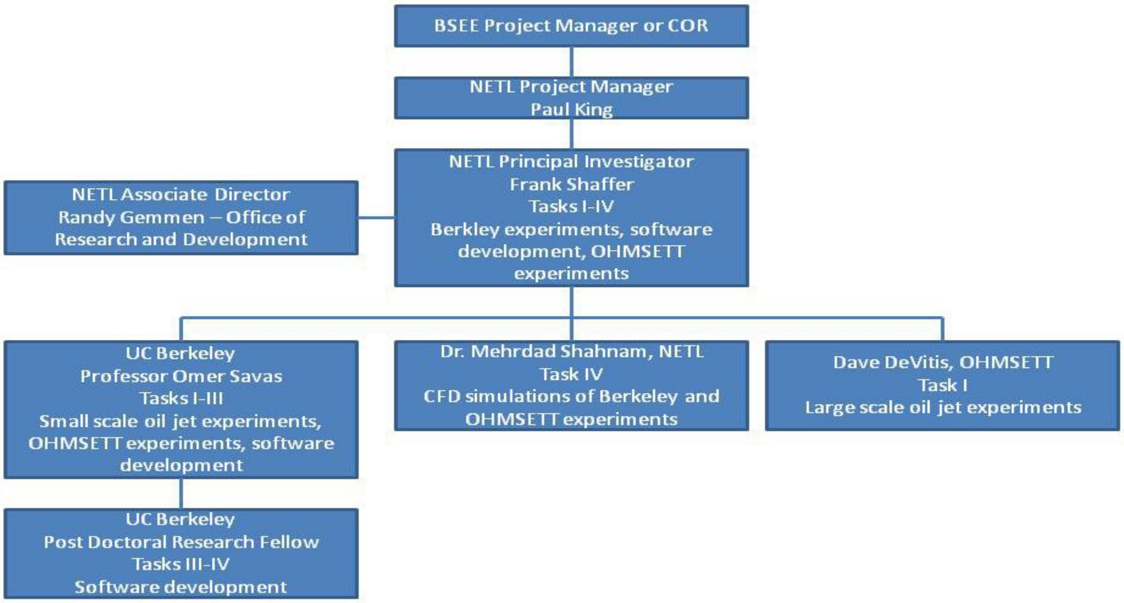
Evaluation of the success of the leak measurement technique and software is covered in Task 3 and the following objectives:

a) Analysis of the experimental results, including comparison with computer CFD simulations
b) Analysis of the performance of automated video analysis software in measuring the flow rate of the OHMSETT and Berkeley oil jet experiments
c) Automated video analysis software

Ultimate success will be to get this technology into the hands of the first responders to submerged oil leaks. BSEE, NOAA, Coast Guard, and oil drilling companies are the primary first responders.

Key Personnel

Frank Shaffer is the lead PI and Technical Coordinator. Professor Savas and Dave DeVitis will be the lead personnel conducting the experiments at UC Berkeley and OHMSETT. Dr. Mehrdad Shahnam will supervise the CFD modeling tasks. Dave Berry is the NETL Technical Monitor. Paul King is the NETL Project Business Manager. Paula Barksdale is the BSEE CO and Tim Steffek is the BSEE COR.



Statement of Project Tasks and Objectives

This project will produce a technology to rapidly and accurately measure the discharge rate from submerged oil leaks. The National Commission on the Deepwater Horizon Oil Spill concluded that underestimates of the oil leak rate caused an inadequate response and caused attempts to cap the well to fail. It is likely that if the oil leak rate from the Deepwater Horizon was known in the first days of the leak, it would have been capped much sooner and the clean up response would have been more effective. The total cost of damages from the Deepwater Horizon is likely to exceed $100 billion. The DWH leak lasted 80 days. If it would have been capped early, the total cost of damages would likely have been an order of magnitude lower.

The main deliverables will be quarterly and final reports, automated video analysis software, documentation on use of the software, documentation describing the measurement of discharge rates from submerged oil leak jets using ROV video. The reports will be provided as requested in the technology assessment and research (TA&R) guidelines in both MS Word and PowerPoint versions suitable for BSEE hardware and software. Any results prepared for presentation or publication will also be sent to BSEE prior to initial submission to the conference or journal.

Task I: Oil Leak Jet Experiments at OHMSETT

To validate the usefulness and accuracy of this approach, experiments must be performed with actual submerged oil jets with sizes and velocities that realistically simulate an actual significant oil leak. As such, the subject approach will be applied to a submerged oil leak jet in the OHMSETT facility. Oil jets of known flow rates will be colored with dye and the visible structures on the jet boundary will be recorded with a high-speed, high definition video camera.

A submerged oil jet of this magnitude that can be studied under controlled conditions is rare. OHMSETT is one of the only facilities in the world able to create such high volume, high flow rate conditions with oil in a controlled environment. Other organizations will be invited to study other characteristics of the oil jet and subsequent oil slick. Because NETL has a large research program in deepwater extraction of fossil fuels [NETL, 2013], NETL will work with BSEE and OHMSETT in inviting organizations to make simultaneous measurements.

Design of Oil Jet Experiments at OHMSETT

The design constraints for the oil jets in the OHMSETT facility are that (1) they must have visible features similar to those of a significant oil leak jet and (2) must stay submerged as long as possible to allow other measurements.

The main similarity parameters for a submerged turbulent jet are the Reynolds number and the Froude number. The Reynolds number is the ratio of inertial to viscous forces and is defined as

$$\Re e = \frac{UL}{\upsilon}$$

where U is velocity, L is a characteristic length, and υ is the kinematic viscosity. For a submerged jet, U is the mean velocity at the jet exit and L is the jet diameter.

The Froude number is the ratio of buoyancy forces to inertial forces and is defined as

$$Fr = \frac{\overline{U}_0^2}{\sqrt{gd\frac{(\rho_\infty - \rho_0)}{\rho_\infty}}}$$

where $\overline{U}_0$ is the mean velocity at the jet exit, g is gravitational acceleration, ρ_0 is the density of the jet fluid and ρ_∞ is the density of the surrounding fluid. The Froude number determines the upward curvature of the trajectory of a horizontally injected oil jet.

Creating an oil jet in the OHMSETT facility with Reynolds numbers matching those of a significant oil leak jet will ensure that their visible features will also be similar. It will also ensure that the process of breakup of oil into droplets is similar to a significant submerged oil leak.

The OHMSETT experiments will be designed to reach the Reynolds numbers of the DWH oil leak jet after the riser was severed on June 3, 2010. The exit diameter of the DWH leak jet was 0.5 m and the kinematic viscosity of the crude oil was measured to be 7 x 10^{-7} m^2/s [FRTG, 2010]. The mean velocity at the jet exit can be calculated using the government's estimate of a discharge rate of Q=53,000 bpd

$$\overline{U}_0 = \frac{Q}{A_{jet\_exit}} = 0.5\ m/s$$

So the Reynolds numbers of the DWH oil leak jet were as high as

$$\Re e = \frac{\overline{U}D_{jet\_exit}}{\upsilon} = \frac{(0.6m/s)(0.5m)}{7x10^{-7}m^2/s} = 325{,}000$$

In the OHMSETT experiments, the Reynolds number of the oil jet will be set by varying the jet exit diameter and the jet exit velocity.

The jet exit diameter and velocity must also meet the requirement that the jet stay submerged for a significant distance to allow other measurements. The oil leak jet will be injected horizontally, or at a slight angle of declination.

Buoyancy forces will cause the trajectory of the oil jet to curve upward. To ensure that the oil jets stay submerged for a significant distance, we will model the trajectory of the oil jet using the closed form analytical model developed by Gore and Jain [1993]. The Gore and Jain model was used by Weiland of NETL [2010] to model the DWH oil leak jet emitting horizontally from the riser before the riser was severed on June 3, 2010 [FRTG, 2010, Appendix 7].

The basic geometry and nomenclature for the Gore and Jain model is shown in Figure 5 for a predicted trajectory in the OHMSETT facility for a jet injected horizontally at a depth of 3 m with a diameter of 1” and a flow rate of 5 GPS.

In the model of Gore and Jain, *s* is the curvilinear coordinate of the jet centerline, *b(s)* is the jet half-width of the jet at any distance s, and $\theta(s)$ is the angle of the jet centerline from the horizontal at any distance s. Gore and Jain derived the following equation for the angle of the jet centerline

$$\tan\theta(s) = \tan\theta_0 + \frac{1}{\cos\theta_0 Fr^* \sqrt{\rho_0/\rho_\infty}}\left[\left(\frac{s}{d}\right) + 2\beta\left(\frac{s}{d}\right)^m + \frac{4}{3}\beta^2\left(\frac{s}{d}\right)^n\right]$$

where θ_0 is the angle of the jet exit relative to the horizontal, $\boldsymbol{\rho_0}$ is the density of the jet fluid, $\boldsymbol{\rho_\infty}$ is the density of the stagnant surrounding fluid, ***d*** is the jet exit diameter, β is a parameter describing the jet divergence angle, and m and n are fitting parameters.

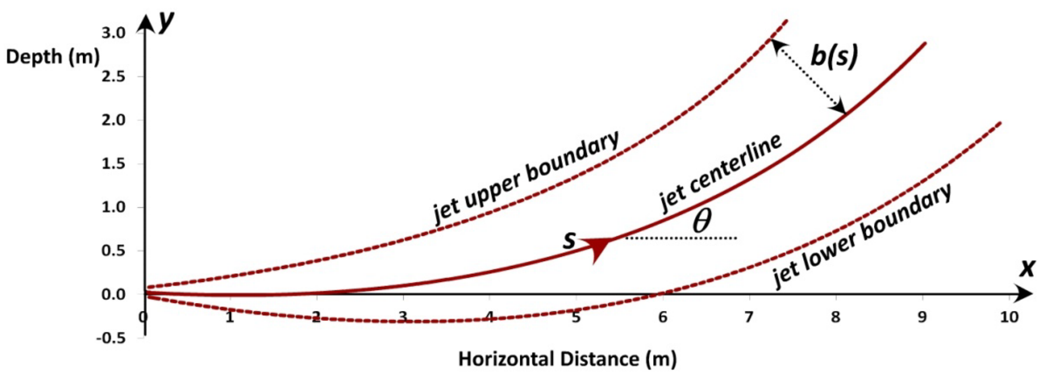


Figure 6. Nomenclature of Gore & Jain model displayed on a prediction of the jet trajectory for a jet diameter of 1" and flow rate of 5 GPS.

The term *Fr** is a modified Froude number:

$$Fr^* = \frac{\overline{U}_0^2}{gd}\sqrt{\rho_0/\rho_\infty}\,\frac{\rho_\infty}{\alpha\left(\rho_\infty - \rho_{jet\_\infty}\right)}$$

where $\overline{U}_0$ is the mean velocity at the jet exit, *g* is gravitational acceleration, *α* is a fitting parameter, and ρ_{jet_∞} is the density of the jet mixture far downstream from the jet exit.

The experimental data of Sharazi and Davis [1972] for a submerged jet emitting into a still body of water was used to determine the values of the fitting parameters, α, β, m and n, for an submerged oil jet in the OHMSETT facility. Figure 6 shows predictions of the Gore and Jain model fitted to the experimental data of Sharazi and Davis. The values of the fitting parameters in the Gore and Jain model are *α=1, m=2* and *n=2 with* β varying from linearly from 0.05 to 0.17 for Fr=5 to Fr=100. The Froude number in the chart by Sharazi and Davis is the traditional Froude number defined above.

To obtain the high Reynolds numbers of a significant oil leak jet, an oil with low viscosity will be used.

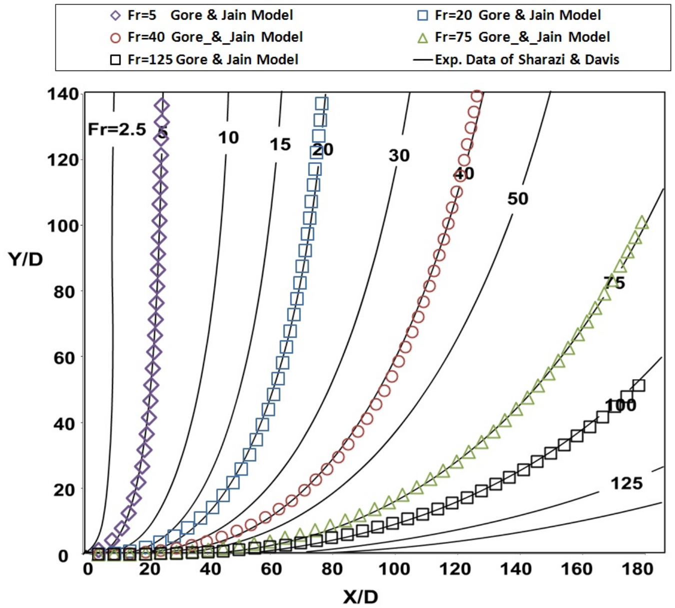


Figure 7. Experimental data of Sharazi and Davis, 1972, for trajectories of buoyant jets injected horizontally as a function of Froude number.

Hydrocal 38 oil with a low kinematic viscosity of 4 x 10^{-6} m^2/s is chosen for our design calculations. This oil is supplied by Calumet Specialty Company (www.calumetspecialty.com) and has a density of 880 kg/m^3. Figures 7-10 show predicted trajectories of an oil jet of Hydrocal 38 injected horizontally at a depth of 0.5 m in the OHMSETT facility. Jet exit diameter ranges from 1" to 2.5", and the flow rate ranges from1 to 10 GPS.

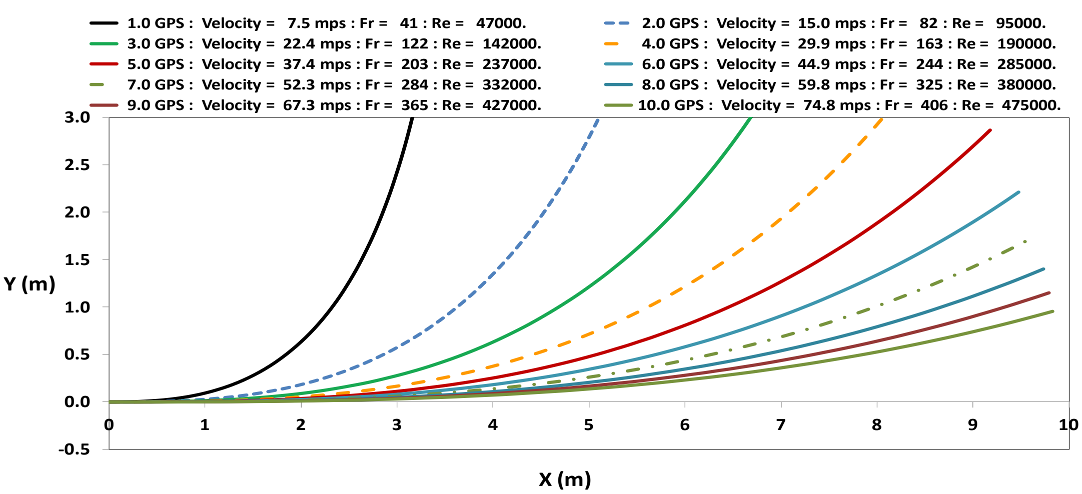


Figure 8. Predicted trajectories for a jet exit diameter of 1.0"

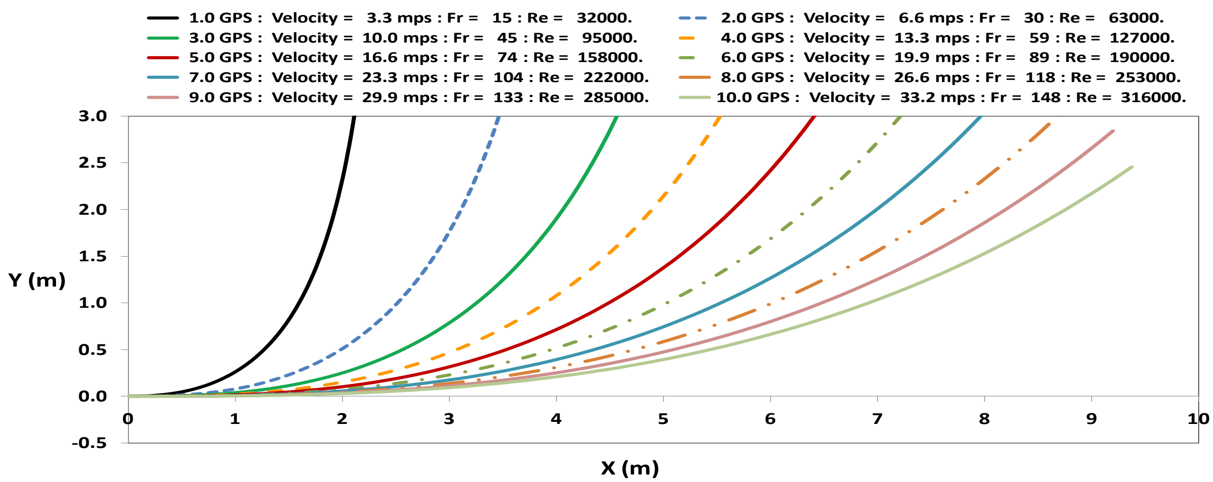


Figure 9. Predicted trajectories for a jet exit diameter of 1.5"

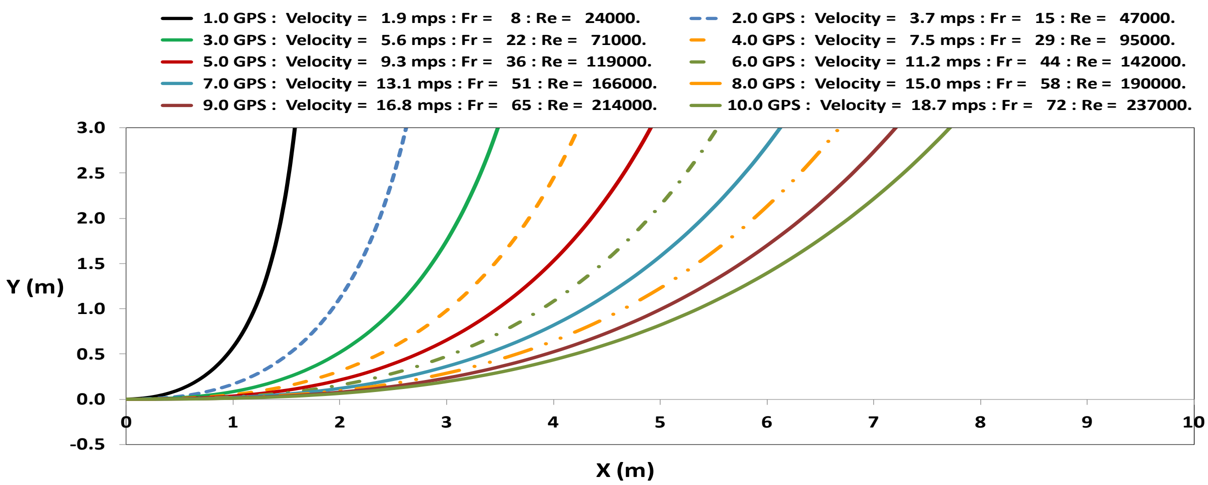


Figure 10. Predicted trajectories for a jet exit diameter of 2.0"

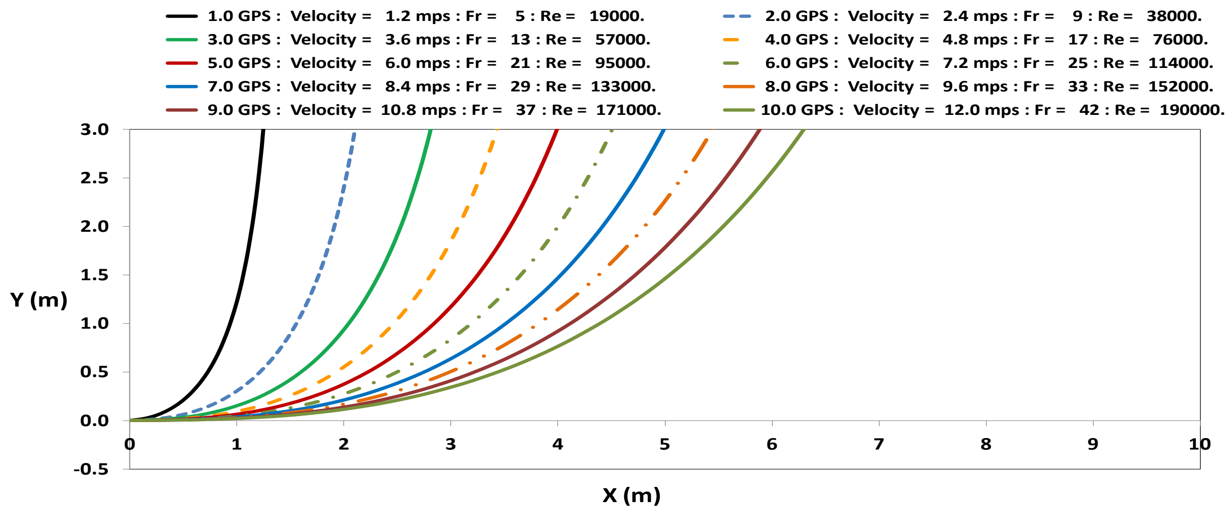


Figure 11. Predicted trajectories for a jet exit diameter of 2.5"

Our goals are to cover a range of Reynolds numbers up to those of the Deepwater Horizon oil leak jet, and to have the oil jet stay submerged for a significant distance to allow other measurements. *Therefore, we propose to use a 2.0" diameter pipe to cover lower Reynolds numbers, from 47,000 to 214,000, and a 1" pipe to produce Reynolds numbers from 237,000 to 332,000. This will achieve the Reynolds number of the DWH oil leak jet and will cover nearly an order of magnitude of Reynolds numbers. The total number of test conditions is eleven.*

The peak Reynolds numbers may need to be slightly lower if the OHMSETT's pumping system cannot produce the required flow rates, or if other measurements by other organizations require lower velocities. For each test condition, two types of dye injection will be used: dye point injection and the oil completely dyed. It should be noted that for our high-speed video, the oil jet only needs to operate at steady state for about ten seconds. This will reduce the amount of oil that needs to be cleaned up after the experiments. However, other measurements by other organizations may require longer operation times for each test condition.

Our experiments with dye colored water jets at the Berkeley Tow Tank have shown that two types of dye injection should be used: point dye injection and full dye injection. With point dye injection, a small tube injects dye near the dye exact. The injection point is scanned from the jet centerline to just outside the jet. With full dye injection, the entire jet fluid is dyed.

Task II: Berkeley Small Scale Oil Jet Experiments

The purpose of small-scale oil jet experiments at Berkeley is to obtain detailed, high-resolution PIV velocity maps of coherent visible features and inside a transparent oil jet. The key personnel for this task will be Professor Savas and Frank Shaffer.

The experiments will be carried out at the 4' x 4' x 8' glass tank in 140 Hesse Hall of the UC Berkeley campus. A schematic of the flow setup is shown in Figure 11. Index matched oil with red dye and PIV seed particles will be discharged from a pressurized accumulator tank. Jet exit diameters and velocities will be chosen so that Reynolds numbers will be high enough to ensure fully turbulent flow.

For PIV mapping of the jet velocity field, the oil and ambient water will be seeded with small particles of low Stokes number. The seed particles will be illuminated by a sheet of high intensity green (532 nm) laser light from an Nd:Yag laser.

The red visible features and green PIV particles cannot be recorded with the same camera because the green laser light from the Nd:Yag laser will be many orders of magnitude brighter than the red dyed jet fluid. Therefore, two synchronized cameras will record the oil jet simultaneously. A high-resolution camera with its line-of-view normal to the laser sheet will record the PIV seed particles and a second high-resolution camera will record the red dyed visible features. Placing a green pass filter in front of the PIV camera will ensure that it only records PIV seed particles and does not see the red dye. A red pass filter placed in front of the camera will ensure that it only records visible features and does not see the green laser light. Thus, the visible features and velocity inside the visible features will be recorded simultaneously.

The small-scale oil jet experiments will allow us to view and measure the velocity of visible features and clearly relate the velocity of visible features to the internal velocity profiles.

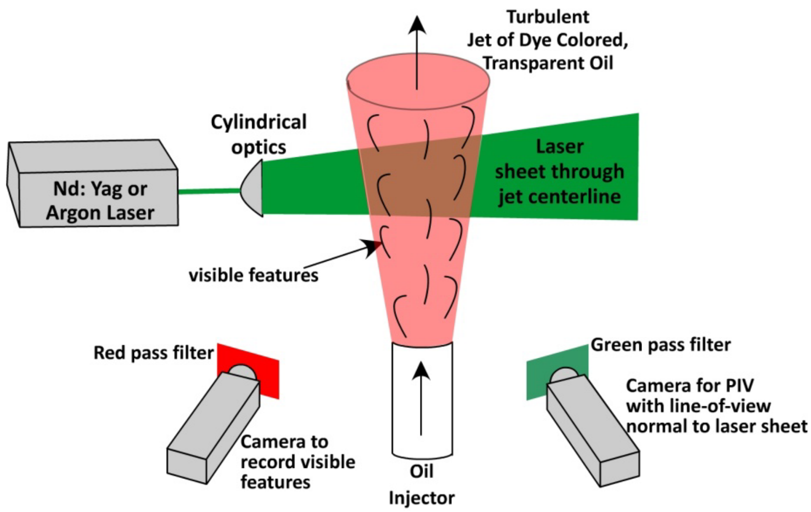


Figure 12. Schematic of flow setup. The tank measures 4 ft x 4 ft x 8 ft. Pressurized air drives the oil jet discharging vertically.

Task III: Development of Software for Automated Measurement of Visible Features

Savas and Shaffer will work together in developing ICV software for automated analysis of ROV video. A full-time post doctoral researcher will also be hired at U.C. Berkeley to assist in the development of the ICV software package. The post doctoral researcher will devote 100Y of his/her time to developing and documenting the software package.

The automated video analysis approach used to measure the velocity of visible features is a category of object tracking called image correlation velocimetry (ICV). With ICV, two consecutive video frames are selected and the second frame is divided into interrogation regions as shown in Figure 12. A smaller "template" region from the first frame is cross-correlated over the interrogation region of the second frame. The cross-correlation can be described as

$$\Phi_{fg}(m,n) = \sum_{m}\sum_{n} f_1(i+m, j+n) g_2(i,j)$$

where $f_1(i, j)$ is the grey level array of template region in frame 1 and $g_2(i, j)$ is the grey level array of the interrogation region in frame 2. The subscripts m and n are the center position of the template over the interrogation region when a cross-correlation is calculated. The result is a correlation peak that measures the average displacement of the visible features from frame 1 to frame 2. With the average displacement and the time between video frames, a velocity vector is calculated for each interrogation region.

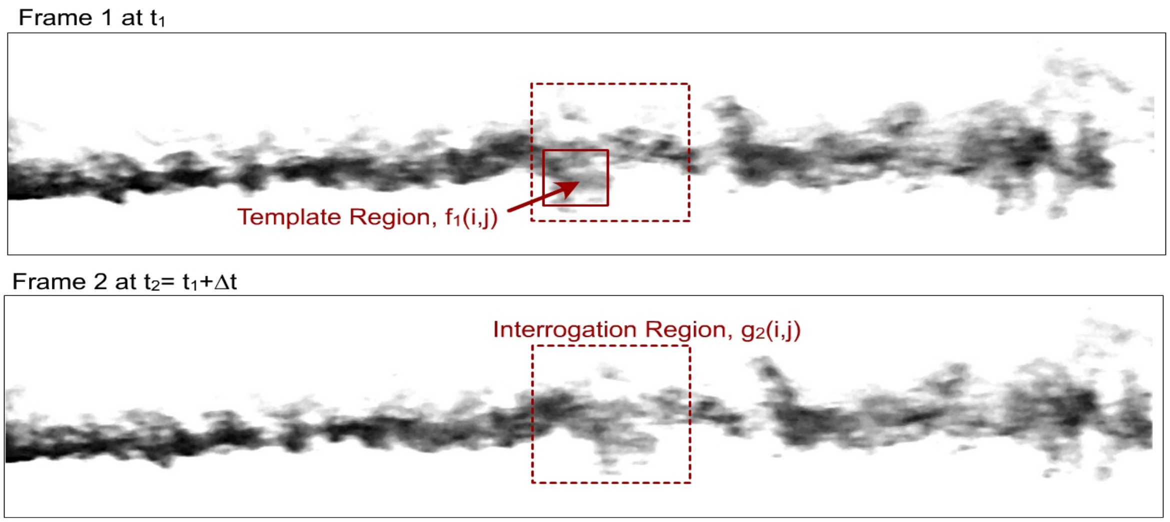


Figure 13. Illustration of template and interrogation regions in two consecutive video frames of dye colored features of a submerged water jet in the Berkeley Tow Tank facility [Shaffer et al. 2013]. Dye point injection was used.

As explained in section 2.3, Savas and Shaffer conducted experiments in 2010 and 2012 with dye colored water jets to simulate the visible features of oil leak jets in the Berkeley Tow Tank facility [Savas, 2012, Shaffer et al., 2013]. They mapped jet velocities with Laser Doppler Anemometry (LDA), a highly accurate velocity measurement technique, and recorded the dyed features with high resolution, high-speed video. The LDA data served as a reference to evaluate the accuracy of ICV.

They found that the ICV can measure the time-averaged velocities of visible features that were in good agreement with LDA velocity data; however, it was also found that ICV results are sensitive to the size of template/interrogation regions. We suspect that the size of these regions needs to be tailored to the size of visible features, but more research is needed to verify this hypothesis. In this project, we will conduct systematic studies of the effect of sizes of template/interrogation regions.

It was also found that ICV results are sensitive to preprocessing steps used to enhance video before ICV analysis is performed. Several preprocessing steps were used, including high pass Fast Fourier Transforms (FFT) to remove variations caused by uneven illumination, contrast enhancement and Sobel edge enhancement. In some, but not all cases, Sobel filtering provided better results.

We also suspect that the accuracy of ICV is dependent on camera frame rates. For the dyed water jet experiments at Berkeley, a high-resolution (2560x1600 pixel), high-speed (1000 frames/sec at full resolution) camera was used and frame rates were set high enough to oversample. Frame rates ranged from 500 per second for the lowest jet velocities to 1500 per second for the highest jet velocities. The higher frame rates may be the reason that ICV worked for the dyed water jets but not for the DWH oil leak jets. The ROV video of the DWH oil leak jets was taken at 25 frames per second.

In the proposed project, the reasons for the sensitivity of ICV results to the size of template/interrogation regions, preprocessing steps, and camera frame rates will be investigated. Systematic studies of the effect of the sizes of template/interrogation regions, preprocessing steps, and camera frame rates will be performed.

We will begin development of the automated video analysis software package by modifying Savas's ALPT software package for this application. The documented software will be made available to the public at the completion of this project. The details of the ALPT ICV approach are briefly described below.

ICV analysis can be computationally intensive. Our ICV analyses of dye colored water jets often required a few hours of CPU time on a high-end engineering PC. The ICV code produced in the project will be optimized for fast processing. There are several proven techniques to reduce the computation time for ICV. One approach is to vary the size of interrogation regions based on velocity gradients of visible features. Where velocity gradients are low, larger (and thus fewer) interrogation regions can be used. The size and number of interrogation regions can be minimized using a multi-pass. Such an approach is first proposed by Huang et al. (1993a, b). Their multi-pass technique yielded improved results for test cases with sharp velocity gradients. Yet another technique is to invoke the species diffusion equation and iterate the velocity field to minimize a suitably defined cost function. Numerous implementations of this approach have been discussed in the literature (e.g. Dahm et al.1992, Tokumaru & Dimotakis 1995).

The Adaptive Lagrangian Parcel Tracking (ALPT) technique developed by Savas et al. treats flow regions as Lagrangian fluid parcels and advects the parcels in the flow-field [Sholl & Savaş 1995, Tsuei & Savaş, 2000]. The ALPT process is illustrated in Figures 13 and 14. Images in two consecutive video frames, *I* and I^+, hence correlations windows used in standard ICV, *f* and *g,* are overlaid at configuration (a). In the ALPT process, we construct a new computational correlation window ~*g* corresponding to the deformed fluid parcel and its sub-parcels in configuration (b).

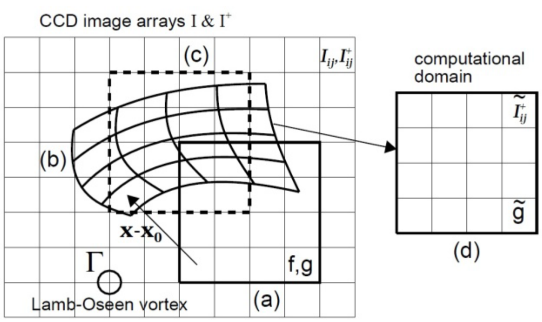


Figure 14. Lagrangian parcel tracking illustrated in the velocity field of a Lamb-Oseen vortex (Sholl & Savaş 1995). (a) Congruent CCD array regions f and g used for ICV. (b) Deformed fluid parcel originally marked by f. (c) Shifted undeformed correlation window for ICV. (d) Reconstructed computational window ~g for ALPT.

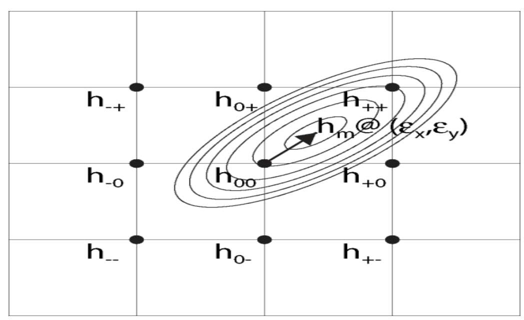


Figure 15. Peak fitting to discrete correlation function hij to determine sub-pixel displacement (εx, εy). h00 is the maximum of hij. Instead of looking for the location and the value of maximum in h(x.y), we look for the location of gradh(x,y)=0 [Sholl & Savaş 1997].

One of the novelties of our implementation of the technique is the method of determining the location of the maximum of the cross correlation for subpixel accuracy, be it Eulerian or Lagrangian. Rather than looking for the location of the maximum correlation value, we look for the location of a vanishing gradient. This approach eliminates curve fitting and allows us the deterministically locate the peak value of correlation. This amounts to fitting an arbitrarily oriented paraboloid or a Gaussian hill to the data as shown in Figure 14.

The modified ALPT software will be applied to video of the oil jets produced in the Berkeley and OHMSETT experiments and to video produced by CFD simulations. Because the velocity fields in the Berkeley experiments and

CFD simulations will be known with high accuracy, they will serve as test cases to evaluate and improve the ALPT software. After optimization of the ALPT software using the test cases, it will be applied to the large oil jets produced in the OHMSETT facility. The goal is to have the ICV software accurately measure the known discharge rates in the OHMSETT experiments. The software package will be documented and made available to the public.

Task IV. CFD Simulations of Submerged Oil Leak Jets by NETL

CFD continues to play a major role as a cost effective diagnostic tool in many areas of engineering. It has been used extensively to study the mixing of immiscible liquids and to simulate flow structures such as the visible features seen at the boundary of oil leak jets. CFD will be used to simulate the oil jet experiments at Berkeley and OHMSETT. CFD will also create simulation videos showing the propagation of visible features in a submerged oil jet. The simulation videos will be used as a test case for the automated video analysis software package being developed for this project.

The CFD simulations will be performed by Dr. Mehrdad Shahnam of NETL. Dr. Shahnam will devote 33 percent of his time to this project. The ANSYS FLUENT code with a Large Eddy Simulation (LES) turbulence model and a Volume of Fluid (VOF) multiphase approach will be used to simulate the Berkeley and OHMSETT experiments.

Figure 15 shows a CFD LES simulation by Dr. Shahnam of the DWH oil leak jet at a depth of 1500 meters. The number of computational control volumes is 2,844,800 and the flow is simulated with 1 ms time steps. The density contours clearly show the visible turbulent eddies at the jet boundary. Figure 16 shows another CFD LES simulation of McIlwain and Pollard [2003] of a submerged turbulent jet at a Reynolds number of 68,000. Coherent vortical/helical structures are shown.

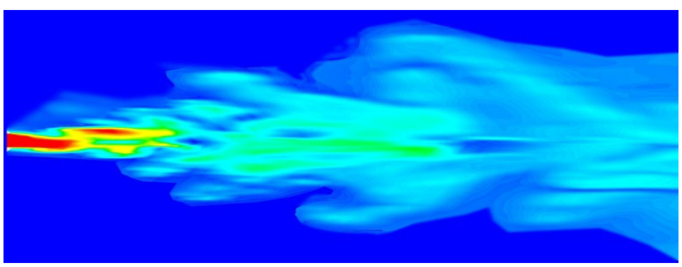


Figure 16. CFD LES simulation by Dr. Mehrdad Shahnam of NETL showing density contours of a submerged buoyant jet. The simulation was done using the FLUENT code running on NETL's supercomputer system. Visible turbulent eddies at the jet boundary are shown.

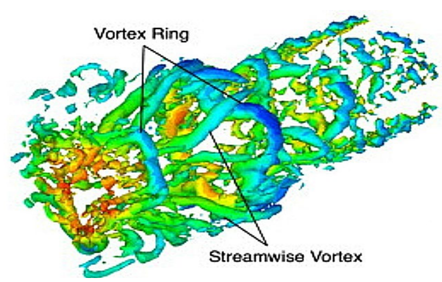


Figure 17. CFD LES simulation showing another view of visible vortical jet features [Ball et al., 2012].

Appendix A: Project Risk Register

RISK REGISTER			
IDENTIFICATION NUMBER (CID):		REVISION NUMBER E.G.; ORIGINAL, 1, 2, ETC.):	Original
RECIPIENT:	NETL Office of Research and Development		
PROJECT TITLE:	Development of a ROV Deployed Video Analysis Tool for Rapid Measurement of Submerged Oil/Gas Leaks		
INTEGRATED PROJECT TEAM (IPT):	PI Name		
• The IPT may vary for each project. Therefore, this list is not to be considered exclusive or all inclusive, and must be modified to reflect the appropriate project assignments. • For ORD Projects, the IPT would consist of the Technical Coordinator, who will obtain input from the Project Controller and Project PI's as needed	Frank Shaffer, ORD Technical Coordinator	Signature	Date
	Dave Berry, ORD Technical Monitor (TMO)	Signature	Date
			Date
			Date
	By above signature, I/We certify that this Risk Register has been made with knowledge of the Program strategic and annual operating plan as specified in any Program Guidance Document given to ORD, the proposed Statement of Project Objectives (SOPO) and Project Management Plan (PMP), and all available historical information (e.g.; past performance prior R&D, etc.).		

PROJECT RISK REGISTER

ATTACHMENT(S):	
• List and attach continuation pages and/or any supporting documentation.	

BRIEF PROJECT DESCRIPTION

Not intended to restate the SOPO, but rather characterize the nature of the project. While the technical objective can be restated, it is important to state whether it is a simple or complex project over multiple years with few or numerous participants, etc.

The main deliverables will be quarterly, draft final and final reports, automated video analysis software, documentation on use of the software, and documentation describing the measurement of discharge rates from submerged oil leak jets using ROV video. The reports will be provided as requested in the technology assessment and research (T A&R) guidelines in both MS Word and PowerPoint versions suitable for BSEE hardware and software. Any results prepared for presentation or publication will also be sent to BSEE prior to initial submission to the conference or journal. The reports will include the following:

i) A summary of the preceding work and overall progress made against the schedule
j) Experimental data from the Berkeley and OHMSETT oil jet experiments
k) Computer CFD simulations of oil jets in the OHMSETT and Berkeley experiments
l) Analysis of the experimental results, including comparison with computer CFD simulations
m) Analysis of the performance of automated video analysis software in measuring the flow rate of the OHMSETT and Berkeley oil jet experiments
n) Automated video analysis software
o) Documentation for use of automated video analysis software
p) Documentation explaining the application of this technology to measure discharge rates from submerged oil leak jets.

PROJECT RISK REGISTER

INSTRUCTIONS FOR COMPLETING THE PROJECT RISK REGISTER	
1.	Although the Technical Coordinator (TC) has primary responsibility for completing these evaluations, the entire Integrated Project Team (IPT) shall participate in the initial and any subsequent changes to the project's assessment.
2.	The IPT may vary for each project. Therefore, the list provided on Page 1 of this Assessment is not to be considered exclusive or all inclusive, and must be modified to reflect the appropriate project assignments.
3.	Each project must first be evaluated using the Assessment of Project Risk Potential to calculate the overall project risk potential. This will determine the level of Risk Assessment and Management to which the project is to be evaluated, monitored and reported.
4.	At the discretion of the TC or other member(s) of the IPT and with appropriate justification, the project may be subjected to more or less Risk Assessment and Management processing than required by the Assessment of Project Risk Potential score.
5.	If, following the Assessment of Project Risk Potential, the project requires further review, it shall be evaluated at each Risk Category to establish a baseline Risk Assessment and Management Plan.
6.	Risk events (i.e.; situations, results, etc.) should be identified for each of the six risk categories. However, it should be noted that not all risk categories may be applicable for each project and/or award type.
7.	When possible, risk events should be associated with the applicable project task, sub-task and/or Work Breakdown Structure (WBS) element, as identified in the Project Management Plan.
8.	Each risk event shall be recorded and numbered in the appropriate section of the Project Risk Register. This will serve as a register of all identified events, including their respective evaluation and management plans.
9.	The Risk Calculation Chart shall be used to assess the Degree of Risk for each event, as well as the level of management required to evaluate, respond, and mitigate that event.
10.	Each risk event shall include identification of the event source (G for Government, R for Recipient or Other), which corresponds to with whom the event will likely occur, as well as assigning responsibility for ensuring that a response and mitigation strategy is defined and approved.
11.	Each risk event shall be evaluated appropriately to determine its full nature (i.e.; cause and likelihood of occurrence) and severity of impact. A resultant response (actions to be taken) and mitigation (steps to reduce likelihood and/or severity) strategy shall be documented.
12.	Following evaluation of each risk event, the TC will assign a Total Degree of Risk for both the category and the entire project. If more than one high risk event is present in any given category, a notation is added assigning a high degree of risk to that entire category. If three or more categories contain high risk events, a further notation assigns a high degree of risk to the entire project.
13.	Examples of risk events which should be considered during the assessment process can be found in the Common Risk Considerations document, located in the Project Management Intranet site. However, this list is not to be considered all inclusive, nor shall each event be relative for all projects.
14.	This assessment is to be considered a "living document," and should be re-evaluated following negotiations, occurrence of a risk event, or changes in project objectives, costs, or schedule.
15.	Routine updates to this document may be accomplished without formal review and/or approval. However, major project occurrences such as those identified herein will require a re-assessment of risk resulting in a revision to this document. Example situations that would require a revision include, but are not limited to:

PROJECT RISK REGISTER

	Continuation Applications Occurrence of a High Risk Event Major changes to Scope, Schedule or Cost
16.	Upon completion of this and any subsequent assessments, M1 must be updated and a copy of this document stored in Adobe Acrobat (pdf) format.

			Consequence				
			Negligible	**Marginal**	**Significan t**	**Critical**	**Crisis**
Probability	**Very High**	>90%	Low	Moderate	High	High	High
	High	75 to 90%	Low	Moderate	Moderate	High	High
	Moderat e	26 to 74%	Low	Low	Moderate	Moderate	High
	Low	10 to 25%	Low	Low	Low	Moderate	Moderate
	Very Low	<10%	Low	Low	Low	Low	Moderate

PROJECT RISK REGISTER

RISK CALCULATION CHART

FINANCIAL

Issues associated with project financing and organizational commitments that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT (Identification & Evaluation of Risk Events) • Description and Evaluation • Probability • Consequence	DEGREE OF RISK (See Risk Calculation Chart) Low Moderate High	RISK MANAGEMENT (Response & Mitigation Strategies) *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
1.1	Other	Cost share funding proposed by partners may not be available to support project objectives, negatively impacting achievement of milestones. Probability: Very Low Consequence: Marginal	Low	The research program included in this project is multi-faceted and this risk relates to one of four or more approaches to achieving the end goals.
		TOTAL CATEGORY DEGREE OF RISK	**LOW**	

Note: Rows may be added or deleted as necessary. If additional space is required for documenting risk event assessments and/or management plans, separate pages may be attached.

PROJECT RISK REGISTER

COST / SCHEDULE

Cost or schedule issues that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT (Identification & Evaluation of Risk Events) • Description and Evaluation • Probability • Consequence	DEGREE OF RISK (See Risk Calculation Chart) Low Moderate High	RISK MANAGEMENT (Response & Mitigation Strategies) *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
2.1	G	Optimistic and aggressive baseline project schedules may result in schedule slippage and cost overruns. Probability: Moderate Consequence: Marginal	Low	The research program included in this project is multi-faceted. Milestones can slip in one or two areas and still achieve overall goals. Monthly technical progress reviews will monitor the progress and recommend changes or additional expertise as necessary to maximize probability of success.
2.2	G	Congressional appropriation throughout FY14 may occur via a Continuing Resolution (CR), which limits cash flow to NETL and, subsequently, NETL-RUA research. This may result in schedule slippage or cost overruns to planned research. Probability: High Consequence: Significant	Moderate	The research program included in this project is multi-faceted. Milestones can slip in one or two areas and still achieve overall goals. Routine technical progress reviews will monitor the progress and recommend changes or additional expertise as necessary to maximize probability of success. In some cases, select research may be focused at the expense of lower priorities if funding is ultimately constrained.
2.3	R	If long lead-time equipment or materials are not identified, ordered, and received timely, then project delays may result. Probability: Low Consequence: Marginal	Low	Long lead time items involve only one of multiple objectives toward obtaining the goals. These items have already been identified and scheduled in the plan.

PROJECT RISK REGISTER

COST / SCHEDULE

Cost or schedule issues that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT (Identification & Evaluation of Risk Events) • Description and Evaluation • Probability • Consequence	DEGREE OF RISK (See Risk Calculation Chart) Low Moderate High	RISK MANAGEMENT (Response & Mitigation Strategies) *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
2.4	R	Recipients not having experience in managing and overseeing large engineering efforts may fail to deliver projects on time and on budget. Probability: Low Consequence: Negligible	Low	DOE, URS, and the RUA have assigned very experienced professionals to conduct the proposed research effort. The work is scheduled in MS Project by element and subtask. Schedules are reviewed and updated monthly in project meetings. Recovery plans are made for tasks that fall behind.
2.5	R	Tasks 2 and 3 – There is a risk that the SECA collaborating teams will not provide timely or complete information to support collaborative research efforts. Probability: Moderate Consequence: Marginal	Low	The TC will regularly meet with team members and facilitate discussion among collaborators to ensure that all members possess a detailed understanding of collaborative needs. In the case key information will not be available on schedule, TC and AM will make arrangements to mitigate impact by supplementing the effort with other resources, supporting a low-deviation work around, or some other acceptable approach.
		TOTAL CATEGORY DEGREE OF RISK	**LOW**	

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PROJECT RISK REGISTER

TECHNICAL / SCOPE

Technical or scope related item that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT **(Identification & Evaluation of Risk Events)** • Description and Evaluation • Probability • Consequence	DEGREE OF RISK **(See Risk Calculation Chart)** **Low** **Moderate** **High**	RISK MANAGEMENT **(Response & Mitigation Strategies)** *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
3.1	R	Significant technical issues may be encountered during the commissioning of research activities, thereby protracting the project schedule. Probability: Low Consequence: Significant	Low	All research activities planned for FY13 are extensions of demonstrated capability, therefore, the risk of encountering a heretofore unknown technical issue is diminished. Furthermore, DOE, URS, and RUA have assigned very experienced engineers and scientists to oversee this research. The same team will resolve emerging issues.
3.2	G	Incongruence of results obtained from discrete research efforts may delay completion of high level research goals that rely on collaborative input from multiple participants. Probability: Moderate Consequence: Significant	Moderate	Collaboration and information sharing will be overseen by experienced technical DOE, URS, and RUA staff, and the team possesses significant experience in successful collaborative activity. The team engages in a regular series of detailed technical exchanges to identify research needs on the critical path and to address deficiencies before they become acute.
		TOTAL CATEGORY DEGREE OF RISK	**LOW**	

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PROJECT RISK REGISTER

ENVIRONMENTAL, SAFETY & HEALTH

NEPA and other ES&H items that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT **(Identification & Evaluation of Risk Events)** • Description and Evaluation • Probability • Consequence	DEGREE OF RISK **(See Risk Calculation Chart)** **Low** **Moderate** **High**	RISK MANAGEMENT **(Response & Mitigation Strategies)** *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
4.1	G	Safety and health employees and the public could be compromised. Probability: Very Low Consequence: Marginal	Low	NETL has an effective Safety Analysis and Review System (SARS) with the necessary elements to identify and mitigate hazards.
		TOTAL CATEGORY DEGREE OF RISK	**LOW**	

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PROJECT RISK REGISTER

EXTERNAL INFLUENCES

Programmatic and other factors external to the project that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT **(Identification & Evaluation of Risk Events)** • Description and Evaluation • Probability • Consequence	DEGREE OF RISK **(See Risk Calculation Chart)** **Low** **Moderate** **High**	RISK MANAGEMENT **(Response & Mitigation Strategies)** *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
5.1	R	NETL's reputation may be damaged due to a recipient's actions such as failing to operate safely, shoddy workmanship, fraud, or causing environmental damage. Probability: Very Low Consequence: Marginal	Low	The RUA universities shall conduct all research in accordance with an established Conduct in Research Plan and/or procedures designed to ensure safety and the accuracy of the R&D results and of all associated documentation. RUA research operations are small with little or no capacity for environmental damage.
5.2	Other	Projects having multiple participating organizations may not be managed effectively resulting in schedule slippage or cost overruns. Probability: Very Low Consequence: Marginal	Low	An experienced professional project manager/technical principle investigator has been assigned as the TC for this project. The TC will actively be engaged in all aspects of the University research, providing the basis for integration of collaborative technology as required in the SOW.
5.3	R	All University conducted Tasks will require retention of expertise in order to ensure milestone completion and/or deliverables. Graduation of students and/or their departure from the university could jeopardize this continuity of technical expertise. The consequence of not having individuals prepared to immediately step in will cause a delay in conduct of the project and possibly missed milestones or deliverables. Probability: Low Consequence: Marginal	Low	After notification to and agreement by URS-NETL, additional student(s) will be trained prior to the graduating student's departure.

PROJECT RISK REGISTER

EXTERNAL INFLUENCES

Programmatic and other factors external to the project that jeopardize realization of project milestones and objectives.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT (Identification & Evaluation of Risk Events) • Description and Evaluation • Probability • Consequence	DEGREE OF RISK (See Risk Calculation Chart) Low Moderate High	RISK MANAGEMENT (Response & Mitigation Strategies) *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
		TOTAL CATEGORY DEGREE OF RISK	**LOW**	

Note: Rows may be added or deleted as necessary. If additional space is required for documenting risk event assessments and/or management plans, separate pages may be attached.

OTHER

Other Project risks which are not applicable to the pre-defined risk categories.

ITEM	SOURCE G, R or Other	RISK ASSESSMENT (Identification & Evaluation of Risk Events) • Description and Evaluation • Probability • Consequence	DEGREE OF RISK (See Risk Calculation Chart) Low Moderate High	RISK MANAGEMENT (Response & Mitigation Strategies) *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
TOTAL CATEGORY DEGREE OF RISK			**N/ A**	

Note: Rows may be added or deleted as necessary. If additional space is required for documenting risk event assessments and/or management plans, separate pages may be attached.

TOTAL PROJECT

TOTAL PROJECT RISK ASSESSMENT	DEGREE OF RISK **Low** **Moderate** **High**	RISK MANAGEMENT **(Response & Mitigation Strategies)** *All High risk events/categories must include a detailed evaluation; response plan; mitigation strategy; and critical oversight (actions to monitor events deemed critical) are required.*
The overall project risk is low. Most of the risks are management, cost, schedule, or technical in nature. Project management systems have been implemented to mitigate known risks in management and cost/schedule areas. Technical risks will be managed by using experienced staff, state of the art technology, and a senior peer review process. For example, ORD will review and oversee UC Berkeley and OHMSETT work, BSEE and NETL EPAct managers will monitor ORD's plans and reports, and technical merit reviews will be conducted by focus area experts.	Low	Mitigation strategies are included with each risk event.

Note: Rows may be added or deleted as necessary. If additional space is required for documenting the Total Project risk assessment and/or management plan, separate pages may be attached.

The following is a sample format for continuation of risk event evaluation and management planning. Although this format is not to be considered mandatory, it does represent the minimum information required for each risk event.

ITEM NUMBER: << As listed in the Risk Register >>

RISK ASSESSMENT: << Complete Identification and Evaluation of the event >>

DEGREE OF RISK: Low, Moderate or High

RISK MANAGEMENT: << Complete Response and Mitigation Strategy for the event >>