Abstract

GexCon, who has teamed with SRI, was awarded Subcontract 12121-6403-01 under the Research Partnership to Secure Energy for America (RPSEA), whereby the objective of this project is to improve inherently safer offshore facility designs. As the size of Ultra-Deepwater (UDW) facilities increases in the Gulf of Mexico (GOM), designs must consider the potential adverse effects associated with vapor cloud explosions in large congested areas and understand the potential for more devastating deflagration-to-detonation transitions (DDTs) on these facilities. Gas derived explosions can expand at over 6,000 feet per second, rendering escape to safety virtually impossible. Therefore, it is critical to understand how a facility’s geometry or equipment layout can affect explosion consequences and assist in their mitigation and/or prevention.

Only recently, post-Macondo, have platform operators placed more emphasis on major explosion barriers between the well head and the people running the very controls needed to control a blowout. Many of the existing drilling platforms have not considered predicting the effects of a small explosion escalating into a major event either in ship design or in prevention, such as what occurred on the Deepwater Horizon. All marine rigs have some fire control method(s), but few have evaluated escalating effects of explosions or DDTs.

Designing topsides structures to withstand credible explosion events and to prevent the potential devastating phenomena of deflagration to detonation transitions (DDT) is an essential part of the route towards inherently safer designs for GOM drilling and production facilities. However, there is a lack of data at the large scale to validate the necessary design tools used to predict the risk of DDT. There are two main factors currently inhibiting inherently safer designs:

- A lack of detailed geometry information in the early design phase, which, when not integrated into facilities designs to identify congestion when performing explosion studies, result in severely underestimated design blast loads.
A lack of adequate tools to predict the potential risks of DDT on these large deep water facilities, where the consequences of DDTs can be orders of magnitude larger than typical deflagrations. One of the main goals of this project is to provide large-scale DDT explosion data and validate the tools necessary to predict vapor cloud explosions in early design phase. The work will also be used to develop guidance documents and recommended practices to facility owners and designers in order to minimize the consequence of explosion incidents.

This paper will present the current updates for the large scale testing being conducted in a newly developed test rig of \(1,500 \text{ m}^3\) (52,000 \text{ ft}^3) gross volume. These tests will involve evaluation of deflagrations and DDTs involving stoichiometric, lean and rich mixtures ethylene, propane and methane. Further phases of the testing will also evaluate the effectiveness of other mitigation measures (e.g., water deluge, solid inhibitor) on the explosion consequences.
Introduction

A large vapor cloud explosion (VCE) followed by a fire is one of the most dangerous and high-consequence events that can occur in petrochemical facilities. The Piper Alpha incident in 1988 was one of the most critical turning points in offshore safety, whereby a relatively minor explosion in the compression module escalated to a massive fire that killed 167 people and destroyed the platform (see Figure 1). This incident demonstrated the need to not only understand explosions, but also the importance of avoiding the escalation of minor incidents into much more devastating consequences. Despite the Piper Alpha incident being a key driver in explosion research and the development of modern risk assessments for petrochemical installations, explosions continue to occur as witnessed by the 2010 Deep Water Horizon incident. The Deep Water Horizon event was the result of a minor explosion on an Ultra-Deepwater (UDW) semi-submersible rig escalated into a massive fire, killed 11 crewmen and led to the largest oil spill in US waters (see Figure 2).

Designing topside structures to withstand a maximum credible event (MCE) is an essential part of the path toward safer designs, which can be achieved by avoiding unacceptable escalation of events and damage to safety critical equipment. This is especially true as the size and complexity of facilities increases. Designs must consider the potential adverse effects associated with vapor cloud explosions in large congested areas and understand the potential for more devastating deflagration-to-detonation transitions (DDTs) on these facilities. Hence, it is critical to understand how a facility’s geometry or equipment layout can affect explosion consequences and assist in their mitigation and/or prevention.
While the likelihood of DDTs is lower than deflagrations, they have been identified in some of the most recent large-scale explosion incidents including: 2005 Buncefield explosion (Bakke, 2010) (Johnson, 2010), 2009 San Juan explosion (U.S. Chemical Safety and Hazard Investigation Board, 2015), and 2009 Jaipur event (Johnson, 2012). The consequences of DDTs can be orders of magnitude larger than deflagrations because they have the ability to self-propagate outside the region of high congestion/confinement and blast overpressures can be up to two orders of magnitude higher for a DDT. Due to the inability to predict such devastating phenomena on the large scale, owners and designers cannot evaluate installations for risk of DDTs and provide “inherently safer” layout or mitigation measures to significantly reduce or eliminate such hazards.

Therefore, two main factors inhibit inherently safer designs: (1) lack of validated design tools to predict risk of deflagration-to-detonation transition (DDT), where the consequences can be orders of magnitude larger than typical deflagrations (determining under what conditions a DDT can occur and what mitigation measures will work are crucial in calculating MCE for offshore facilities); and (2) lack of detailed geometry information identifying congestion in the early design phase, which results in severe underestimation of design blast loads when not accounted for in explosion studies.

GexCon, who has teamed with SRI, was awarded Subcontract 12121-6403-01 under the Research Partnership to Secure Energy for America (RPSEA), whereby the objective of this project is to provide tools to enable the construction of inherently safer offshore facility designs, specifically addressing the technology gaps presented above. The objective of the project is to address the two above mentioned technology gaps by: (1) improving, adapting, and validating the tools necessary to predict MCE early in the design phase of Gulf of Mexico (GOM) UDW facilities and (2) providing guidance and recommended practices to facility owners and designers which, when utilized, will help minimize and design against the consequences of fire/explosion incidents.

In order to achieve such goals, GexCon will perform large-scale experiments to validate DDT onset prediction and active mitigation at scales relevant to large-scale designs. These studies will be used to further validate and develop industry-accepted CFD tools and simplified methods, which are currently used to evaluate the consequences of explosions in the oil/gas industry (Arntzen, 1998) (Puttock, 2013) (Van den Berg, 1985) (Tang, 1999).

Definitions.

- **CFD** – Computational Fluid Dynamics
- **Deflagration** – Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium
- **Detonation** – Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium
- **DDT** – Deflagration to detonation transition
- **ACM** – Anticipated congestion methodology
- **GOM** – Gulf of Mexico
- **UDW** – Ultra deepwater

Description of DDT Testing and ACM Methodology.

To facilitate the design of “inherently safer” facilities, we need to predict the maximum credible event (MCE) for vapor cloud explosions and evaluate how design changes affect the possible consequences. Determining whether a deflagration-to-detonation transition (DDT) can occur is imperative for accurate calculation of MCE. Currently, there is a lack of adequate tools that can predict DDT in oil and gas
facilities, especially at the large scale that is most common to UDW facilities. To address this problem, GexCon US has teamed with SRI International to further develop and validate the DDT onset prediction capability of GexCon’s FLACS CFD package and other analytical tools, and to investigate mitigation techniques that can reduce the consequences of VCEs on UDW facilities through large-scale experimental testing. To address the issue of accurate predictions of explosion consequences early in the design phase, we are working to develop an anticipated congestion methodology (ACM) as well as a congestion database for as-built and early phase platforms designed for ultra-deepwater facilities in the Gulf of Mexico. GexCon developed the original anticipated congestion methodology (ACM) using North Sea facilities and successfully applied it to over 60 facilities.

Figure 3 illustrates our basic approach. We are currently working on validating FLACS and other analytical tool’s DDT onset prediction capabilities for scales and geometries relevant to GOM UDW structures. FLACS is a commercially available code that is currently used by over 100 companies. To judge the likelihood of a DDT occurring during a deflagration event in a congested environment FLACS monitors the spatial pressure gradient across the flame front at any location at any moment. The value of this spatial pressure gradient is normalized using the grid resolution and initial pressure reading:

$$
\left. \frac{dP}{dx} \right|_{\text{normalized}} = \left. \frac{dP}{dx} \right|_{\text{actual}} \frac{X_{CV}}{P_0}
$$

where $P_0$ is the initial pressure and $X_{CV}$ represents the grid resolution. A magnitude of the pressure gradients of order 1 indicates that DDT is likely, with values around 10 or larger indicating a strong possibility of DDT (Middha, 2008) (van Wingerden, 2008).

In order to achieve the goal of validation, we have developed a large-scale test facility of approximately 1,500 m$^3$ gross volume at a joint GexCon/SRI test site to study the potential of DDT for gases of varying reactivity (i.e., methane, propane, and ethylene) and will utilize the large-scale experimental data for FLACS and other analytical tool’s validation. The tests will be conducted with various levels of congestion, confinement, and gas concentrations. The flame speed and overpressure measurements will be used for validation. Also, we will perform experiments that utilize mitigation measures (e.g., water deluge, solid inhibitor) to reduce the explosion consequences. The FLACS software will be updated and enhanced empirical models will be developed from the validation studies to extend their application to the large scale.
To enable prediction of explosion hazards in the early design phases (concept or FEED phase), GexCon is working to further develop their ACM for GOM offshore drilling and production facilities. This methodology will define what levels of anticipated congestion are necessary to supplement CAD models in early design phase to ensure accurate assessment of explosion hazards. We will first provide numerical test results (explosion pressure and ventilation) for GOM topside structures that have detailed “as-built” CAD models. We will then gradually reduce the design detail of the “as-built” model and provide the explosion pressure and ventilation as a function of object density and design detail. Next, we will take CAD geometry models in early design stages (for the same topsides) and gradually implement anticipated congestion to evaluate explosion blast loads, then compare results with those obtained for detailed “as-built” design. We will adjust the ACM until the CAD models in early design stage have congestion levels sufficient to produce overpressures that match those from the final fully detailed models. The results of this project will provide oil and gas companies operating in the GOM the tools necessary to design “inherently safer” offshore facilities that can survive VCE incidents and prevent escalation, already when the project is in the early design stages. As these tools will be available early on, designers will be able to make design changes and have detailed explosion overpressure information early in the design phase, which can minimize costs by avoiding pitfalls and changing designs in late phases.

Data and Results.

Large-scale Testing.
GexCon combined with SRI to develop a joint large-scale explosion area at SRI’s 480 acre CHES site in California. A large-scale test pad was constructed in January 2015, which covered a test area approximately 10 m x 60 m. An overview can be found in Figure 4. This test pad was designed for continued use after the proposed RPSEA test matrix. Several thermocouples are also embedded within the concrete for use in potential spill tests in the future. The testing site also includes adjacent open area for supplemental testing to be conducted regarding exposure to overpresssure events. This could include testing of structural response of elements exposed to overpressure or similar tests for near-field overpressure exposure.
As part of the testing plan, GexCon and SRI have developed a modular test assembly. This will allow for extensive flexibility in the testing, whereby congestion levels and congestion orientations can easily be modified within the rig. Several design iterations were evaluated to ensure the durability of the rig. The plan is to create an array of these modules with 2 modules across, 15 modules deep and 1 module high as shown in Figure 5. The rigs were designed using Finite Element Analysis to withstand numerous DDT events without permanent deformation or damage.

To assist in understanding the size of these modules and the final test volume, please refer to pictures (Figure 6 and Figure 7) of the modules during construction and final assembly onsite. As the goal of the project was to easily modify congestion levels and congestion orientations within the rig, hundreds of approximately 7-inch and 2-inch pipes were purchased and delivered to the test site (see Figure 6) to be added into the base modules to increase and vary congestion levels.
A single polyethylene sheet of 0.1 mm (0.004 in) thickness covering the modules was used to retain the gas/air mixture prior to ignition. A steel plate was welded along the upper and lower most structural elements, and ran the entire length of the module assembly. The polyethylene sheet was secured directly to the modules along these plates. An electric spark was used as the ignition source and was located approximately half a module length within the structure, centered and at mid-module height.

Gas was introduced into the rig at four separate locations and mixed thoroughly with numerous box fans. Samples were extracted at 8 locations throughout the rig, with half the sample points being located in the upper section and half near ground level. The extracted samples were sequentially pumped to an IR gas analyzer (IR4800D three channel), which was calibrated prior to the test. Commercial grade propane (HD-5, >95% purity) was utilized for the initial tests. After uniform concentrations were established in the rig, the fans were stopped for 2 minutes, after which the mixture was ignited.

The flame progression was captured using two to three high-speed video cameras (Phantom V7.2) and two normal speed cameras. One set of high-speed and normal speed cameras was located perpendicular to the propagation direction of the flame located and the other set just offset of the parallel axis (see Figure 8). The high-speed video was run typically at 10,000 fps (40 µsec exposure) and was used to determine flame arrival and flame speed for the tests. Test #6 included an additional high-speed camera setup for a close-up view of the initial flame development in the first few rows of modules. The high-speed video data is used to provide a very accurate flame-front location as a function of time from which the flame speed can be determined.
Thirteen ionization pins were also utilized to capture the flame propagation within the modules as shown in Figure 9. Upon flame arrival, the presence of ions in the reaction zone lowers the resistance across the sensor gap initiating a capacitive discharge where the resulting transient voltage is detected. Ideally the time of arrival measurements between successive pins can be used to determine the flame speed.

The overpressure development within the test rig polyethylene enclosure was measured using 13 pressure transducers located along the major axis, nominally flush with ground level and coupled with the ion pins within the rig (see Figure 9). There are 4 other pressure transducers outside the rig, two along the major axis and two perpendicular to the anticipated DDT location (not pictured). The PCB types 113A36 and 112M343 pressure transducers with built-in FET amplifiers were used. The 113A36 type has a range of 0-34.5 bar and a response time of 1 µs, while the 112M343 has a range of 0-6.9 bar and a response time of 2 µs. The modules start with row four (as shown in Figure 9) for tests #5 and #6 due to 24 modules being used out of a possible 30. An additional pressure transducer and ionization pin will be placed in module row number two during the future full 30 module tests. Two weather stations (Davis 6152 Vantage Pro 2) were utilized at the test site site to record, temperature, wind speed, wind direction and humidity at the time of the test.

![Figure 8–High speed camera angles in red, regular speed in orange.](image-url)
To verify the strength of the modules, preliminary detonation tests using stoichiometric propane-air mixtures were conducted exposing only two modules (see Figure 10). An explosive charge was used to initiate a detonation in the propane mixture to test the rigidity of the modules. No permanent deformation was observed in the initial testing, confirming the FEA analysis and strength of the module design.

Testing is ongoing to evaluate three fuels of varying reactivity under three levels of congestions. The expectation is that the highest reactivity fuel (ethylene) will transition to DDT in the lowest congestion level, the medium reactivity fuel will transition to DDT in the medium congestion, and to evaluate the likelihood of methane DDT in high congestion. The proposed test matrix is shown in Table 1. With the remaining time and budget, we plan to investigate active mitigation measures such as deluge or solid inhibitors.

Table 1—Proposed initial test matrix. Tests highlighted in green to be conducted first, yellow second and red last. Tests marked with an asterisk will be repeated if DDT is achieved.
Test Results.

The first two tests (tests #5 and #6) were conducted with 24 modules (two modules wide and 12 long) and with commercial grade propane (HD-5) as a fuel. The gross volume for these tests was approximately 1,200 m³ (42,000 ft³) with dimensions of approximately 8 m wide by 48 m long and 4 m tall. The specifications for HD-5 fuel grade propane are a minimum of 95% propane. A sample of the fuel will be analyzed after each test to verify its content. At the time of this report, the results are still being analyzed. Pending the results of these nearly full-scale tests, the test matrix may be edited to reflect any new information brought to light by the test results.

The congestion level was in the “low” configuration with no pipes added and a resulting low volume blockage ratio (e.g., volume occupied by the obstacles divided by the volume of the rig) of 5.8%. The results of the first full-scale test resulted in a DDT approximately half way down the rig (see Figure 11 through Figure 13). A repeat of this test, using a different batch of commercial grade HD-5 propane, similarly resulted in a DDT; however, the DDT occurred approximately two modules further down the rig (see Figure 14 through Figure 16). The initial flame development for the deflagration is shown in Figure 17. Figure 18 shows the measured flame position versus distance also confirm that the two tests transitioned at slightly different locations, and after transition, result in flame speeds of approximately 1700 m/s close to the theoretical Chapman Jouget detonation velocity.
Figure 11–Test #5 camera screen capture.

Figure 12–Test #5 high-speed video screen captures of the DDT (side view)
Figure 13–Test #5 high-speed video screen captures of the DDT (back view)

Figure 14–Test #6 camera screen capture.
Figure 15–Test #6 high-speed video screen captures of the DDT (side view)

Figure 16–Test #6 high-speed video screen captures of the DDT (back view)
Figure 17–Test #6 high-speed video screen captures of the initial flame development of the deflagration
In parallel to the experimental campaign, a preliminary study was conducted on various congestion levels using FLACS CFD software. Over 300 CFD calculations have been executed for rig congestion optimization and included running sensitivities on grid cell size, time step (CFL numbers), and pipe sizes and pipes needed per row of congestion. Preliminary FLACS results indicate that a DDT is predicted for congestion levels as found in the experiments. These results are however preliminary and are currently being further investigated.

**Anticipated Congestion.**

The idea behind the anticipated congestion task was to bridge the gap between explosion overpressure predictions at early design phase with as-built platforms. From our experience, the resulting overpressure can differ by one to two orders of magnitude depending upon the congestion level present in the early phase designs. Figure 19 illustrates three different design phases, Concept, Feed and EPC. Each of these shows a resulting higher overpressure loads from CFD simulations performed with each geometry level of detail.
In order to help bridge the gap between these early and late geometries, GexCon has proposed to investigate this in two styles. The “top-down” approach will focus on starting with as-built geometries and slowly remove pipes smaller than 2 inches, then 4 inches and onward to evaluate at which point predicted overpressures will begin to deviate significantly from those predicted using the as-built geometry. The “bottom-up” approach will start with early concept and FEED phase geometries and begin to add in anticipated congestion. The anticipated congestion is planned to include both random pipe placement and more detailed pre-built skid placement meant to represent the congestion levels that would be present at an as-built completeness.

GexCon has begun to run congestion counts and evaluate overpressures on completed as-built geometries from our extensive library using the above outlined methodology. In addition, our cost-share partners Total, Shell and Chevron have each provided a handful of installations, of varying completeness from FEED to As-Built, which are currently being imported into the CASD preprocessor and added to the ACM database (details follow). Overviews of some as-built geometries can be found below in Figure 20.

These models are currently being setup for the necessary ventilation and explosion simulations. Simulations have begun by removing various levels of congestion (e.g., below 2-inch, below 4-inch, etc.) and evaluating the explosion consequences.

In order to help assess final as-built congestion levels and compare those values with information available in early design phase requires comparison with numerous as-built facilities. GexCon is
undertaking efforts to document as many platforms as possible and populate an ACM database. Within this database will be details for each section of an offshore installation and will include various details such as designer, throughput, year built, owner/operator, process type, location, etc. This database will be easily modified and amended as necessary, and also will include functionality to re-run congestion counts for future releases or developed congestion quantification schemes. Some early screenshots of the ACM database development can be found in Figure 21. This database will be available both as a plugin to the FLACS preprocessor CASD and as an independent database. A preliminary database is completed and functional. Minor updates have been planned as the project continues. Currently the database is being populated as platforms become available.

Conclusions

Large scale testing began in December 2015 with planned tests running approximately every other week for the next several months. The preliminary work indicates that DDT’s at large scales may be easier to obtain than from previous experiments performed in smaller test rigs. This work will provide critical validation blocks upon which future tools can be developed. Once developed, these tools can help owners and operators plan inherently safer layouts and platforms that mitigate the risk of high consequence events. Work is also ongoing for the anticipated congestion tasks with GexCon’s in-house as-built library and platforms provided by the project cost-share partners.

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References


