SANDIA REPORT
SAND2014-0905
Unlimited Release
Printed February 2014

Cost Estimate for a Proposed GDF Suez LNG Testing Program

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Abstract

At the request of GDF Suez, a Rough Order of Magnitude (ROM) cost estimate was prepared for the design, construction, testing, and data analysis for an experimental series of large-scale (Liquefied Natural Gas) LNG spills on land and water that would result in the largest pool fires and vapor dispersion events ever conducted. Due to the expected cost of this large, multi-year program, the authors utilized Sandia's structured cost estimating methodology. This methodology insures that the efforts identified can be performed for the cost proposed at a plus or minus 30 percent confidence.

The scale of the LNG spill, fire, and vapor dispersion tests proposed by GDF could produce hazard distances and testing safety issues that need to be fully explored. Based on our evaluations, Sandia can utilize much of our existing fire testing infrastructure for the large fire tests and some small dispersion tests (with some modifications) in Albuquerque, but we propose to develop a new dispersion testing site at our remote test area in Nevada because of the large hazard distances. While this might impact some testing logistics, the safety aspects warrant this approach.

In addition, we have included a proposal to study cryogenic liquid spills on water and subsequent vaporization in the presence of waves. Sandia is working with DOE on applications that provide infrastructure pertinent to wave production. We present an approach to conduct repeatable wave/spill interaction testing that could utilize such infrastructure.

Foreword

"Contained herein is a Rough Order of Magnitude (ROM) cost estimate that has been provided to enable initial planning for this proposed project. This ROM cost estimate is submitted to facilitate informal discussions in relation to this project and is NOT intended to commit Sandia National Laboratories or its resources.

Furthermore, as a Federally Funded Research and Development Center (FFRDC), Sandia must be compliant with the Anti-Deficiency Act and operate on a full cost recovery basis. Therefore, while Sandia, in conjunction with the Sponsor, will use best judgment to execute work and to address the highest risks and most important issues in order to effectively manage within cost constraints, this ROM estimate and any subsequent approved cost estimates are on a 'full-cost recovery' basis. Thus, work can neither commence nor continue unless adequate funding has been accepted and certified by DOE."

Due to the scale and expected costs of this large, multi-year program, the authors have utilized Sandia's structured cost estimating methodology applicable to large programs over $20M in size. The cost estimates and project approval was coordinated and approved by the appropriate line organization Vice President. The methodology and the associated management oversight provided will ensure that the costs of the construction and testing identified in the proposal would fall within a -30% to + 50% range of the proposed costs.

For the size of this test program, and with the range of hazards associated with it, it is expected that at least a year of planning, design, and construction will be required. As the program directions mature and testing needs are reevaluated and finalized, value engineering efforts will be incorporated to better define and solidify a final cost proposal. These efforts would be done in close collaboration between Sandia, GDF, and their industry partners.

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1. GDF REQUEST AND PROGRAM OBJECTIVES

GDF SUEZ (Gaz de France or GDF), through their Research and Innovation Division, has been involved in conducting and organizing experimental testing and the development of fire and dispersion models for Liquefied Natural Gas (LNG) spills for many decades. Their LNG experimental testing includes 35-m in diameter pool fires at the Montoir test site (1000 m^2 in a concrete bund) in partnership with British Gas, British Petroleum, SHELL, and TOTAL, medium-scale pool fire tests (in-house, with pool diameters between 1 to 20 m), fires with foam addition, dispersion (instantaneous releases, pool vaporization, etc.), spillage and vaporization (pool spreading on different ground surfaces), rapid phase transition research (Lorient and Montluc), jet fire testing, and participation in several Joint Industry Program (JIP) efforts addressing jet dispersion, cloud fires, and vapor cloud explosions. They have developed or used a range of fire and dispersion hazard prediction models including both simplified in-house models (EVOLCODE) and more sophisticated models (including PHAST, FLACS, KFX, ORDER, LSMS, LNGfire3, etc.).

Because of Sandia National Laboratories' (Sandia's) past experience in LNG spill hazard modeling and testing, GDF approached Sandia in September 2013 to consider supporting an industry funded large-scale LNG spill, dispersion, and fire testing program. The drivers for this testing program are to improve hazard modeling and safety considerations of large, non-confined, LNG spills from a growing range of water and land-based spill scenarios, including:

- LNG liquefaction and export facilities and power plants spills,
- ground transportation spills – railroads, trucks, isotainer accidents, and
- transportation fueling infrastructure associated spills.

GDF requested Sandia provide an estimate of costs to design, manage, and conduct this test program by December 2013. GDF had estimated that the program could cost on the order of $20-25M over 3 - 4 years. In support of this testing program, GDF will be organizing an international industry consortium to help fund the effort, including potential industry leaders such as – British Gas, British Petroleum, Shell, TOTAL, GAZPROM, etc.

1.1. Relationship of Proposed GDF LNG Testing Program with Previous LNG Work

The purpose of the proposed GDF LNG spill test program is to conduct larger fire and dispersion tests to extend the testing data base and improve the ability of fire and dispersion models to accurately address larger LNG spills, especially those on land. This will help improve future hazard analyses and help facilitate and accelerate LNG infrastructure siting nationally and internationally. The proposed testing is necessary due to the current gaps between experimental LNG spill data and the postulated worst case spill scenarios. For example, the largest dispersion test was a 202 kg/s spill with a duration of 131 s (66 m^3); whereas the worst case spill scenario GDF believes should be considered is a 1000 to 1800 kg/s spill lasting 10 to 30 min (1300 to 7000 m^3). Likewise, for LNG pool fires the largest tests on land had a pool diameter of 35 m. The largest test on water was an 83 m diameter spill resulting in a 56 m diameter pool fire. The potential worst case spill for major transportation accidents on land or at an export terminal could yield a pool diameter greater than 100 m. Similar issues and concerns exist for jet-type dispersion events and jet fires.

Many release scenarios involving LNG (offshore releases, pressurized storage, large spills on land, etc.) will require better models that are validated with new experimental results (dispersion: temporal and spatial concentration levels, etc., fire: SEP, flame length, etc.) to better estimate hazards and public safety needs. The proposed work supports new land-based uses of LNG, focuses on data gaps for land-based spills, and includes fire and dispersion testing, analysis, and modeling. The GDF testing program would focus on unconfined LNG fires and dispersions on land for the following reasons:

- There is no data on unconfined (fuel not contained in a berm) LNG fires representative of emerging spill scenarios and volumes,
- There is no test data on dispersion hazards for LNG spills on land for the scale of interest,
- There is no experimental data on National Fire Protection Association (NFPA) requirements to dispersion distances to ½ the Lower Flammability Limit (LFL) for vapor concentration on either land or water – only to LFL distances on water, and
- Large scale data is needed to validate land-based spill hazard modeling and analysis.

The proposed GDF testing program also includes large LNG fire and dispersion testing on water that would supplement previous DOE and Sandia testing efforts. Large fires on both land and water would lead to better understanding of soot formation that is necessary to improve hazard modeling and analysis. Similar to the large dispersion tests on land, collecting data on water dispersion vapor concentrations to ½ the LFL would help improve compliance modeling.

There is also a request for conducting tests to determine wave impacts on LNG spill dynamics on water. Since Sandia has investigated the development of testing infrastructure to provide reproducible wave sizes, frequencies, and spectral data to test wave energy technologies for the DOE renewable energy research and development programs, Sandia was asked to consider developing a cost proposal for evaluating LNG spill interactions on water with waves. This area of research has not been conducted at any realistic scales to date, and is be a new area of LNG spill research.

1.2. GDF Requested LNG Test Program

Table 1 presents the proposed GDF LNG spill test program. Currently, a total of twenty tests (not including the zero phase testing intended for equipment functionality verification, calibration, etc.) are proposed. This includes ten dispersion tests, five on land and five on water, and ten fire tests, also five on land and five on water. Vaporization and cloud dispersion on land and water at these scales would provide steady state spills from 1-3 minutes (70-200 m^3 spills) to 5-10 min (1500 m^3 spills).

Table 1. Requested GDF LNG Test Program

Phase	LNG dispersion	LNG pool fires
Zero	1-10 m^3 : equipment and sensors tests on land and water	1-10 m^3 : equipment and sensors testing on land and water
1	4 releases of 70 m^3 (rate 500 kg/s) : 2 releases on land, 2 releases on water	4 releases of 70 m^3 (rate 500 kg/s) : 2 releases on land, 2 releases on water
2	4 releases of 200 m^3 (rate 500 kg/s) : 2 releases on land, 2 releases on water	4 releases of 200 m^3 (rate 500 kg/s) : 2 releases on land, 2 releases on water
3	2 releases of 1500 m^3 (rate 1000 kg/s) : 1 release on land, 1 release on water	2 releases of 1500 m^3 (rate 1000 kg/s) : 1 release on land, 1 release on water

GDF's identified first priority is to collect data on LNG dispersion with the goals to:

- evaluate LNG spreading and vaporization on water (including wave effects),
- understand scale affects for very large LNG cloud dispersions,
- obtain accurate data on LFL distances, cloud height and width, and
- evaluate LNG dispersion at low wind (high stability) conditions.

The identified second priority is to collect LNG pool fire data to better understand:

- soot formation mechanisms for large fires on land and water, and
- water vaporization impact on LNG fires on water.

1.3. Required Test Site Characteristics

The test sites capabilities needed to safely conduct the GDF requested LNG spill tests need to meet the following requirements:

- provide storage capacity to hold a minimum of 1500 m^3 of LNG,
- have the ability to receive and store LNG from tankers in a safe and secure manner,
- be able to release the stored LNG at discharge rates of up to 1000 kg/s,
- protect equipment and personnel from fire and thermal hazards,
- protect equipment and personnel from large vapor dispersion hazards (requires an estimated minimum 2 km and up to 4 km diameter exclusion zone during testing), and
- test and assess the impact of waves on LNG spill dispersion on water.

The pool fires tests (both on land and water) will require a pool diameter of ~120-150 m.

The dispersion tests on land will require a pool diameter of ~100 m. A large shallow water pool of ~200 m in diameter is needed for the largest dispersion test on water.

Additional requirements identified to meet the needs of GDF include:

- flat and hard "smooth" spillage areas characterized to understand the vaporization potential of the surface,
- a readily available source of water (able to provide 1-2 million gallons of water) for the pool fire and pool dispersion tests,

- ability to provide overhead coverage of the testing, such as towers, balloons, drones, helicopters, aerial flyovers, and/or satellites,
- ability to field a very large array of instruments with appropriate communication and data rate capabilities,
- ability to obtain National Environmental Policy Act (NEPA) categorical exclusions or Environment Assessment (EA) approvals, and
- allow foreign nationals to support and witness test construction, setup, and tests.

1.4.Requested Data Collection and Test Measurements

Table 2 presents GDF's requested primary list of parameters for test measurements and test data collection. This table was utilized in developing the proposed testing area locations, schedule, instrumentation set-up, and instrumentation and testing support. In some cases, the instrumentation is available at Sandia to collect the data requested, while in other instances new instrumentation will need to be purchased and installed. In many cases, Sandia considered a number of data collection approaches, both traditional and emerging new instrumentation technologies, to collect the required data.

Table 2. GDF LNG Spill Experiment Data Measurement Needs

Desired GDF Test Parameters	**Pool Fire**	**Dispersion**
Released Mass flow rate	x	x
LNG composition	x	x
LNG temperature inside discharge pipe (if possible)	x	x
LNG temperature at orifice	x	x
Velocity of liquid inside discharge pipe (if possible)	x	x
Water temperature at several depth	x	x
Vapor composition inside LNG vapor cloud		x
Vapor concentration around evaporating pool		x
Size of flammable cloud		x
Size of visible cloud	x	x
Wind measurement: direction, speed (several heights and positions)		x
Solar radiation		x
Cloud coverage	x	x
Ambient pressure and temperature	x	x
Flame temperature and emissivity	x	
Flame heat flux / Surface emissive power	x	
Process Equipment Parameters		
LNG storage tank pressure	x	x
LNG storage tank temperature	x	x
LNG storage tank liquid level	x	x
LNG storage tank liquid temperature	x	x
Nitrogen source for tank purging/pressurization	x	x

2. PROPOSED SANDIA LNG SPILL TESTING APPROACH

Sandia has significant experience with both small-scale and large-scale LNG spills and fire and dispersion (propane) testing and modeling over the past 10-20 years. This work has been conducted for a number of U.S. agencies including the Department of Energy (DOE), the Coast Guard (USCG), as well as other groups**.** Additionally, Sandia has over 50 years of fire science modeling, testing and analysis in support of many U.S. energy and weapons programs**.** This expertise makes Sandia uniquely qualified to conduct the requested GDF LNG spill and hazards testing effort.

Sandia proposes to conduct the pool fire tests at our LNG fire experimental site in Albuquerque. These tests would be conducted first since much of the test infrastructure and data acquisition infrastructure are already in place. While we considered also conducting the dispersion tests at the same location, the estimated 4 km (diameter) safety zone necessitates that a more remote location is utilized. In the sections below we provide detailed discussions on our suggested approaches to meet the specified testing and data collection requirements for the fire, dispersion, and wave impact testing requested.

2.1 Pool Fire Testing Approach

2.1.1. Sandia Pool Fire Testing Experience

The proposed GDF test program complements prior Sandia LNG safety and security work, noted below in Table 3. Sandia has demonstrated the capability to perform both small-scale and large-scale LNG pool fire tests**.**

Table 3. Previous Sandia LNG Experimental Fire Testing

Test Series	LNG release / pool fire	Notes
1	10 releases (200 gal tank, 4 kg/s): equipment and sensors on land and water	WFO/ Industry 2004
2	2 releases (10,000 gal tank, 6 kg/s): equipment and sensors on land and water	LNG/LPG WFO Study 2004
3	30 releases (FLAME facility) 3-m diameter gas burner fire tests to determine flame height to diameter ratios	DOE/USCG Study 2008
4	1 release of 58 m^3 (rate 48 kg/s): equipment and sensors on land and water	DOE/USCG Study 2009
5	1 release of 199 m^3 (rate 802 kg/s): equipment and sensors tests on land and water	DOE/USCG Study 2009

For the DOE/USCG study, Sandia constructed an experimental area to conduct up to 100 m diameter LNG pool fires on water with the ability to collect data on surface emissive power (flame radiant energy), fuel vaporization rate (pool size), and flame height. The experimental setup (shown in Figure 1) and test results are extensively detailed in "The Phoenix Series Large Scale LNG Pool Fire Experiments," SAND2010-8676.

Figure 1. Sandia Large-Scale LNG Pool Fire Experimental Site

2.1.2. Pool Fire Test Siting

The current Sandia LNG fire test site in Albuquerque is proposed to conduct the requested GDF pool fire tests. To address issues and lessons learned from the Phoenix test series, we propose to procure eight transportable 208 m^3 cryogenic LNG isotainers (ASME-rated pressure vessels) to provide the required storage capacity (see Figure 2). The use of these tanks is proposed since they can be designed to meet the required capacity and flow rate requirements, can be used for both the dispersion and fire tests, and will have a salvage value or use after the test series. For the pool fire tests they would be sited next to the water pool at the Phoenix test site, and either the existing reservoir would remain or be removed if deemed necessary (Figure 3). For both cases, the existing discharge piping and dirt berm inside the water pool would be removed to minimize extraneous impacts on the pool fire test results.

The eight large cryogenic cylindrical tanks (9% Ni steel) would be constructed and shipped to the test site. The tanks would then be insulated after delivery. High pressure compressed gas (nitrogen) tube trailers, shown in Figure 2, would be used to provide the pressure source needed to force the LNG out of the tanks during each test. The estimated cost for the eight tanks including insulation and plumbing is approximately $5M. Note these tank systems would be available for reuse in the future either by Sandia, GDF, or their industry partners.

This use of these tanks would address the high boil off rate associated with the current LNG storage reservoir at Sandia. With the large volumes of LNG that will be required for the pool fire tests, ways to more efficiently fill and store the LNG are needed. With this approach, more tanks can be filled simultaneously, and less boil off can be insured. In addition, this approach allows the use of large cryogenic remotely-operated valves, which in conjunction with the high-pressure nitrogen source pressurizing the tanks, will improve the spill control and enhance discharge flow rate measurements for the tests. Simplified incompressible flow calculations (no flashing or head/friction loss assumptions) determine a tank pressure of 6 psi is needed to discharge 1000 kg/s though an 18 inch pipe. Calculations will be refined if the proposal moves forward. A notional drawing of the eight tank layout is shown in Figure 2. A radiant shield steel cover (shown in one picture) will surround the tanks for fire protection.

For the pool fire tests on water, the existing large shallow water pool (120 m diameter, 0.3 m near the edge, ~2.0 m in the center) would be slightly expanded and used for all three LNG pool fire test phases. For the pool fire tests on land, the water would be drained and the soil compacted to create a hard surface, or a thin artificial surface (possibly 1 cm of gunnite) could be applied to the test area for the same purpose. The use of gunnite is recommended for cost reasons. In order to replicate soils similar to onshore facilities, we will need to have detailed soil properties that will then determine the thickness of concrete, thermal and surface properties (smooth, rough), need for rebar, etc.

Phase 1 requires either a 20 m diameter area with a bund (20 cm tall wall) or a 50 m diameter free spillage area. Phase 2 requires a 35-40 m diameter area with a bund (20 cm tall wall). Phase 3 requires a 100 m diameter area with a bund (20 cm tall wall). All three test phases can be conducted at the current Phoenix test site.

It is believed that the proposed GDF scenarios are indicative of a point source spill, that precludes the need to discharge to the center of the pool as was required in the Phoenix series for DOE and the USCG. Therefore, a short discharge pipe would be used to release the LNG at the pool edge, allowing a steady progression of the liquid to proceed across the pool, which more closely simulates a point source spill.

This approach reduces the need to rework our current LNG storage reservoir to address the high boil off issue, and reduces the cost of constructing a second storage reservoir for the dispersion tests. The proposed tanks can be used for both tests. Additionally, the tanks are then available for a wide range of other tests, or allow more flexibility to modify or change future tests based on the initial testing results.

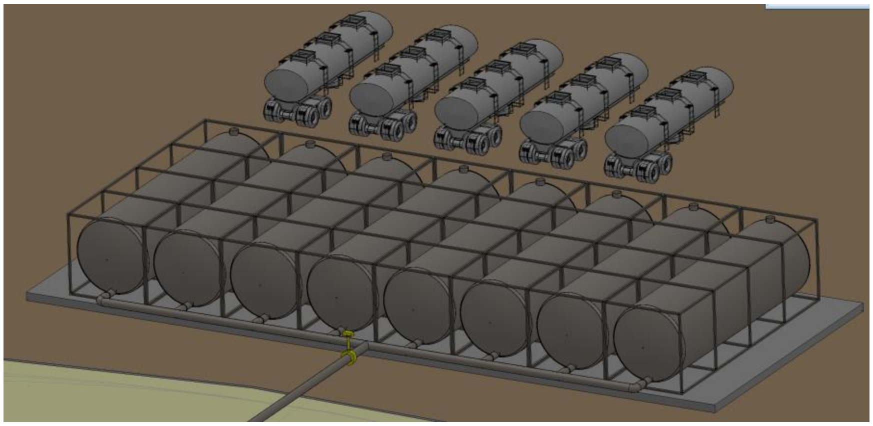

Figure 2. Large Capacity LNG Isotainers

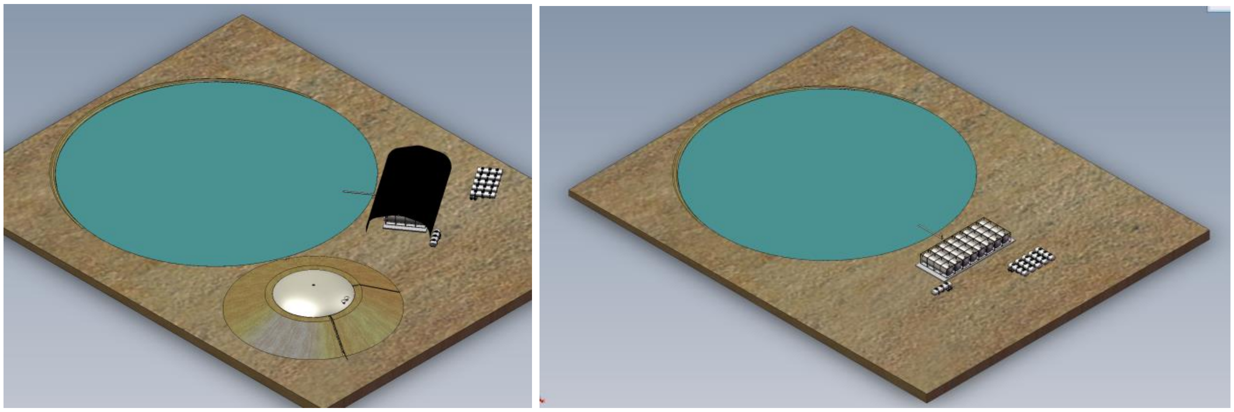

Figure 3. Isotainers at Phoenix Series Test Site (with and without existing reservoir)

Benefits to using the existing Sandia LNG pool fire test site include extensive on-site LNG testing resources (personnel and infrastructure), minimal travel costs, Kirtland Air Force Base helicopters that can provide aerial support, and easy access to laboratory experts in state-of-the-art photometrics, imaging techniques, etc.

The key enabling concept for the success of the Phoenix test series was a safe, low-fabrication-cost experimental testing area. The creative solution necessitated significant operational safety considerations including unprecedented cooperation between numerous Sandia organizations, the DOE Sandia Field Office, and Kirtland AFB agencies (including flight-operations and emergency fire-response). These safety, operational, and cooperative agreements are still in place to support the GDF LNG spill tests.

Significant, first-principles-based, environment, safety, and health analyses would be used to provide confidence that the test design and operations are safe. Safety during testing will be primarily ensured through limited access and extending hazard zones to 900 m surrounding the pool. Safety issues to be examined include tank and associated plumbing integrity, thermal (cryogenic to fire fluxes), asphyxiation, explosion, drowning, and aviation operations (helicopter and airport traffic). Advanced transient, three-dimensional transport simulations will be used to evaluate both the thermal performance of the storage tanks and components and the transport of gaseous boil-off during the cool-down process.

There was an extensive suite of permits and approvals (Table 4) for the construction and the operation of the Phoenix test series of LNG pool fire experiments. Based on preliminary discussions with Sandia's and DOE's Environmental Health and Safety organizations, the renewal of any necessary permits and the associated approvals should be relatively straightforward and are not expected to cause any delays in the testing schedule.

Table 4. Previous Phoenix LNG Series Permits, Reviews, and Approvals

Title
NEPA – SNA07-0195 – Large Scale LNG Spill Tests - DOE Approved for Categorical Exclusion
Biological Survey
Excavation Permit
Fugitive Dust Permit – 10090626-3732
Storm Water Pollution Prevention Plan
PHS - SNL07A00147-001 - Large Scale LNG Tests - Moderate Hazard Classification
Burn Permits: Approved by City of Albuquerque
Aviation Operations - requests for aviation support and aviation safety plans, approved by NNSA and FAA, MOA with KAFB 58th/SOW
Water Discharge – City (Albuquerque) and State
DOE ISMS - IWP1662 - Large Scale LNG Pool Fire Experiments - Management Operational Review
Process Hazard Analysis
Management Self-Assessment
PSM Pre-Startup Safety Review

2.1.3. Pool Fire Test Setup and Proposed Instrumentation

This section describes the measurements necessary to meet the experimental data needs. Pool fire instrumentation would be very similar to what was used in the Phoenix LNG series.

Note that not all of the instrumentation described below is included in the ROM costs. This additional (or possibly alternate) instrumentation was considered and is presented as an opportunity to consider new state-of-art technology. This instrumentation would be a first time use for data collection at the scales required and therefore will require some feasibility testing in Phase 0 prior to utilizing the technologies in later test phases. However, this advanced instrumentation technology could significantly improve the quality and quantity of data collected.

The following is a general summary of the primary instrumentation to be utilized. Measurements will likely be based on four cardinal axes or “spokes” that currently surround the spill area.

- Instrument towers (4) (210 m from pool centerline)
- Data Acquisition Systems (DAS)
- Storage Tank liquid level (8 capacitance or similar gauges)
- Storage Tank internal liquid/gas temperature (8 thermocouples (TCs))
- Storage Tank internal pressure (2)
- Storage Tank flow rate (1)
- Spill area (overhead video (2))
- Heat flux to pool surface (directional flame thermometers)

- Water temperature (TCs)
- Plume height (4 HD cameras) (2 infrared)
- Spectrometers (4) (400-800 nm, 1300-4800 nm)
- Heat flux / SEP (radiometers: narrow-angle (16), wide-angle (16)
- 3D ultrasonic wind speed/direction (4)
- Ambient pressure/temperature/relative humidity (1)

Below we provide detailed information on each of the instrumentation systems we would use and their capabilities.

Data Acquisition Systems (DAS) and DAS Network

The data acquisition system (DAS) consists of five PCs with 16-bit data acquisition cards connected to a National Instruments (NI) SCXI-1001 chassis. A typical chassis has twelve NI SCXI-1102 cards with NI SCXI-1303 blocks for TCs and four NI SCXI-1104 cards with NI SCXI-1300 blocks for analog signals. This provides the ability to increase either analog signals or TC signals. Note that the SCXI-1001 can hold 12 cards, yielding a total channel count of 384 channels if all slots were used for data acquisition. The system is upgradeable simply by adding an additional SCXI-1001 DAQ card and more multiplexer units (MUXs).

Flame Heat Flux - Narrow-angle Radiometers

Narrow-angle radiometers measure the "spot" incident heat flux at various heights of the flame plume surface (Medtherm Schmidt-Boelter sensors, 12 mV nominal at 300 kW/m^2, 5.5º view angle, with zinc selenide window, water cooled, 63.2% time constant is 35 ms). These would be mounted with co-aligned cameras on pan/tilt mounts operator-controlled to allow precise tracking at the desired flame location.

Flame Surface Emissive Power (SEP) - Wide-angle Radiometers

Wide-angle radiometers measure the radiant heat flux (Medtherm Schmidt-Boelter sensors, view angle of 150º, with zinc selenide window, water cooled, 63.2% time constant is <500 ms). To support the wide-angle radiometer analysis, four HD video cameras (one at each tower location) would be positioned to have nearly the same view as the wide-angle radiometer in order to capture the flame plume shape and allow converting the incident heat flux to a "flame-average" SEP.

Pool Heat Flux

The total incident (radiative and convective) heat flux to the pool surface would be measured with directional flame thermocouples (DFTs) attached to a stand in the pool that places the DFTs ~6-12 inches above the water surface.

Fuel Regression Rate

The fuel regression rate is a calculated parameter determined by dividing the measured transient mass flow rate from the storage tanks by the measured transient liquid pool area and this represents an average value over the whole area of the pool. Mass flow to the pool is inferred from tank liquid level changes (Guided Wave Radar, capacitance, or other means) and would also be measured using flow meters (Annubar or ultrasonic) in the discharge piping.

Photometric Coverage Pool Area

Overhead video would be used to determine the real-time extent of the spreading pool fire. The overhead video could utilize manned four-axis LSG-2 gyro-stabilized mounts flown on two Kirtland AFB helicopters. Also attached to the stabilized mounts are Sony™ HDW-750 high definition video camcorders.

Photometric Coverage - Flame Height

Four real-time cameras (Canon Vixia HD MiniDV real time camcorders (30 Hz)) with zoom lenses identically adjusted would measure the flame height. These cameras, paired with the wide-angle radiometers on each spoke, determine the average surface emissive power of the fires. Cameras will be located on the end of each spoke (~226 m) focused on the pool vertical centerline. Additional cameras will provide Flame Height, Smoke Plume, Site Surveillance Long Range, and Full Plume Capture views.

Infrared cameras

Infrared data would be acquired using FLIR Systems™ model S-60 and SC-660 infra-red cameras with uncooled microbolometer detectors, utilizing 450 FOV lens. The S-660 (640 x 480 pixel array) and the S-60 (320 x 240 pixel array) are located at a distance of 214 m from pool center. These cameras are sensitive to the wavelength band of 7.5-13 micrometers.

Ground-Based Spectroscopy Instrumentation

Mid-infrared spectral radiation intensity measurements would use imaging spectrometers (model ES-200, Spectraline, Inc.) The Sandia-owned (3 units) ES-200 measures spectral radiation intensity at 390 Hz in the 1.3 to 4.8 micron wavelength range and each of the pixels looks at a wavelength of 22 nm. The total wavelength range accounts for 75% of the emitted radiation energy from a blackbody source at 1420K. The view angle of the stationary spectrometer is ±0.27 degrees. The ES200 spectrometers are equipped with a 1D scanner. The scanner is capable of measuring a line with 128 pixel resolution in just 0.32 seconds.

Ground-Based Spectroscopy Instrumentation (optional- not included in ROM costs)

The FTIR is a Sandia-owned Fourier Transform Interferometer manufactured by ABB – Bomem in Québec. The MR304 can be configured with two separate channels, one with a mercury-cadmium-telluride (MCT) detector and the other with an InSb detector. With both channels, the instrument is capable of measuring the spectral region from 1.0 to 15.0 μm with a spectral resolution of up to 1 cm^{-1}; the data is then used to determine flame temperature and emissivity. The instrument could be used with the narrow angle telescope to have a field of view (FOV) of 4.9 mrad. The nearest focusing range for the narrow angle telescope is 30 meters and the range for the field collect will be over 1 km. Sandia has used this system for large fires and collected interesting and improved information on fire combustion products and associated fire processes.

A Sandia-owned thermal imager could be used in conjunction with the FTIR and is a microbolometer based camera that has a broadband response from 8-12 μm. The field-of-view of the instrument is approximately 26° by 19.6°. The camera can output images at a rate of 30 frames per second. A LabView® GUI and data acquisition software application was developed to allow streaming of video straight to hard disc over an IEEE 1394 interface.

Meteorological Instruments and Support

Meteorological data (wind direction and velocity, temperature, relative humidity and barometric pressure) would be measured and recorded with near-field instruments fielded by the Fire Sciences and Technology Department and with instruments fielded by the Meteorological Monitoring Program at Sandia. The SODAR operating frequency is 4504 Hz and the maximum height setting for this support is a nominal 200 meters. The LNG tower would be instrumented to measure temperature, relative humidity, wind, and atmospheric pressure. Wind and temperature will be available at both the 10 meter and 29.3 meter levels. The tower would be instrumented with the same type of instruments that are used in the CAN Meteorological Tower Network at Sandia.

Near pool wind measurements would be provided on the wind towers (~210 m from pool center). Wind speed and direction will be measured at 2 m, 5 m, and 10 m heights using YOUNG 81000 Ultrasonic Anemometers. Barometric pressure would be measured using a Setra Model 278 Barometric Pressure Sensor (or equivalent). Relative humidity would be measured using a CS HMP45C Temperature and RH probe (or equivalent) with an integral radiation shield.

Temperature Instrumentation

Temperatures within the flame would be measured with an insulated stainless steel pole in the pool (location TBD) upon which 1/16th inch diameter MIMS (mineral-insulated, metal-sheathed (Inconel)) type-K thermocouples (TCs) and DFTs are attached. The temperature of the pool water would be measured using 1/16th inch diameter MIMS type-K thermocouples attached to each of the DFT stands. The temperature of the LNG would be measured using 1/16th inch diameter type-T MIMS thermocouples.

2.1.4. Pool Fire Testing Cost Elements

Table 5 summarizes the cost estimates for materials, purchases, and subcontracts for services for performing the proposed ten GDF LNG pool fire tests on both land and water. Table 9 in section 5 provides the overall summary cost estimate for both the pool fire and the dispersions testing. That overall summary cost estimate includes Sandia labor, overhead, and required taxes for

detailed test planning and cost estimation, work project agreements, work planning and controls to meet environmental safety and health requirements, permits, pretest analysis and modeling, project management, travel, data acquisition programming, instrumentation calibration, and experimental setup at both the Phoenix test site and the remote dispersion test site in Nevada.
The labor estimates in Table 9 for the pool fire tests assume manpower to support ten tests at ten days/test and posttest data analysis and reports.

Included in Table 5 are costs for instrumentation, construction of the LNG storage tanks, site rework, and the costs of the LNG for the tests. The baseline cost for one LNG storage tank is ~$365,000, and x8 is ~$3M. Insulation, plumbing, valves, etc. is estimated to be $500,000. The remaining $1.5M in costs includes the labor to install the tanks and the purchase and labor to install the steel metal structure covering and protecting the tanks from the fire heat flux. Note these tanks are used for both the pool fire tests and the dispersion tests. While flexible in considering options to reduce cost, the one constraint we have is that the tank(s) need to be either constructed on site or they need to be road transportable. The road transport was the factor that limited us to the ~208 m^3 prefabricated tank.

It should be noted that the proposed LNG storage tanks will be portable and can be moved to other sites and will have a salvage value at the end of the test program.

Table 5. ROM Hardware/Purchases/Subcontracts Cost Estimate for Siting Fire Tests

Pool Fire - Hardware/Purchases/Subcontracts for Services	**Cost ($US)**
Meteorological DAQs 4 Towers	$95,000
Storage Tank DAQs	$92,000
Pool DAQ	$37,000
Aerial coverage all tests	$83,000
Pan Tilt 1 - 9 stations / 3 locations for radiometers/SEP measurements	$217,000
Pan Tilt 2 - 1 station / 2 locations for spectrometer measurements	$46,000
Meteorological Support	$35,000
Photometric Cameras (9)	$77,000
Storage Tank Procurement & Install	$5,000,000
Storage Tank Shipping	$273,000
Shotcrete Lining for Water Pool	$237,000
Remove existing water pool discharge piping	$100,000
LNG procurement for pool fire tests	$1,624,000
Total	**$7,916,000**

2.1.5. *Pool Fire Testing Safety and Engineered Safety Considerations*

As mentioned above, the fire tests will be conducted at Sandia's remote, large-scale, testing area where the Phoenix LNG pool fire tests were conducted. This location has been specifically designed for the testing of hazardous materials. As such there are significant operational safety controls in place in this test area.

The Phoenix LNG pool fire test series also required the development of a significant number of engineered safety measures to address a range of potential hazards including wildland fires, reservoir integrity and leaks, thermal (cryogenic to fire) hazards, asphyxiation, explosion, drowning, and aviation operations (helicopter and airport traffic). These existing engineered safety measures and established safe operating plans will continue to be utilized for these tests as appropriate. But these safety plans will be reassessed and modified in collaboration with GDF safety representatives and Sandia ES&H representatives as needed to address additional safety issues and challenges identified during the final planning and design phases that could occur for the larger pool fire tests, the new pool fire configuration, and the new LNG storage and release valves and spill pipelines that will be used. Those engineered safety measures will undergo a thorough safety review before testing operations commence. The program design and construction schedule allows for a comprehensive evaluation of all safety and engineered safety systems and operations prior to testing.

2.2. Dispersion Testing Approach

Sandia's Albuquerque experimental test site was evaluated to perform the LNG dispersion experiments (free spillage on hard soil and on a shallow water pool). Due to the anticipated size of the unignited flammable vapor cloud, the diameter of the hazard zone for the largest experiment is estimated to be ~2 km. This 2 km hazard zone safety distance for the dispersion tests worst case scenario (1500 m^3 spill) is based on CFD calculations for the Hadera deep water LNG port in Israel performed by A. Luketa. The calculation results indicated an LFL of 1100 m for a spill rate of 815 kg/s and pool diameter of 96 m. Thus, for the 1000 kg/s test being considered it is estimated that the LFL should not exceed 2000 m and most likely would be closer to 1500 m based on the results for Hadera.

Unfortunately, the nearest inhabited building distance is less than 1.5 km from the proposed Phoenix spill site. Therefore while smaller dispersion tests could be conducted in Albuquerque, another location will be needed for the larger dispersion tests to accommodate the estimated hazard zone. The following sections present notional information on our proposed test locations, test design, and experimental setup approach for the dispersion experiments.

2.2.1. Sandia Dispersion Testing Experience

Sandia has conducted a number of small scale dispersion tests over the past 40 years. The largest tests conducted used 500 gallons of propane. These tests were conducted by members of the proposed Sandia GDF LNG test team at both Sandia's Tonopah Test Range and in Albuquerque in the early 1990's. The largest vapor flumes measured were approximately ½ km long by about ¼ km wide. These plumes were ignited with explosives to create both vapor cloud fires and detonations. The safety zones for the explosive tests were quite large and were the reason many of the tests were conducted at Tonopah. One explosive test was conducted in Albuquerque and caused a sonic boom that was heard across much of the city.

2.2.2. Dispersion Testing Considerations

For the dispersion tests, a large flat area (~200 m in diameter) would be needed for the free spillage on both land and water. For the land spillage, the expected diameter of the spreading LNG pool is 65 m, 95 m, and 190 m, respectively, for the three different proposed releases. For the water spillage, the expected diameter of the spreading LNG pool is 95 m, 130 m, and 150 m, respectively, for the three different proposed releases. For the LNG spill and dispersion on water, a shallow water pool (200 m diameter, ~0.3 m depth) formed on a large flat area using a small dike or bund (20 cm tall) could be used for all three release events.

The 0.3 m water depth is an initial estimate that requires further analysis and will be performed if the project proceeds. The analysis performed to date is a transient heat conduction calculation predicting the thickness of ice formation for the 1000 kg/s spill, which is approximately 2.5 cm. Penetration depth and mixing was not included in the analysis. These effects are expected to decrease the bulk temperature of the water, particularly in regions near the spill point. Thus, it may be necessary to increase the water depth in those regions. .

In reviewing the GDF needs and the expected associated safety exclusion zones, it appears that conducting the large dispersion tests in Albuquerque would not meet Sandia's minimum safety requirements. Therefore, Sandia considered other options for conducting the large LNG dispersion tests. This would require a second test site and the associated infrastructure for LNG storage. Therefore, portable LNG storage tanks that could be transported and used at both sites is an attractive operational and cost savings alternative, and is one of the major reasons for considering the use of portable LNG storage tanks.

After completing the pool fire test series and possibly the small dispersion tests, the eight portable and modular cryogenic liquid storage tanks used in the pool fire tests could be shipped to the remote dispersion test site. These tanks would be sited adjacent to the free dispersion spillage area, as noted in Figure 4, again precluding the use of a long discharge pipe. Note the tank and associated process equipment would very likely be engulfed in the vapor cloud during the testing depending on wind and stability conditions. The flammable vapor cloud is expected to harmlessly disperse into the atmosphere in less than one hour. As in the fire tests, a radiant shield would be constructed to surround the tanks for fire protection in the unlikely event of a vapor cloud ignition. If this occurs, the vapor cloud would burn back to the pool and then produce a pool fire. Figure 4 shows the test concept, with the eight prefabricated tanks adjacent to a 200 m diameter spill area (the circles within the spill area denote the estimated size of the LNG spill on a shallow water pool).

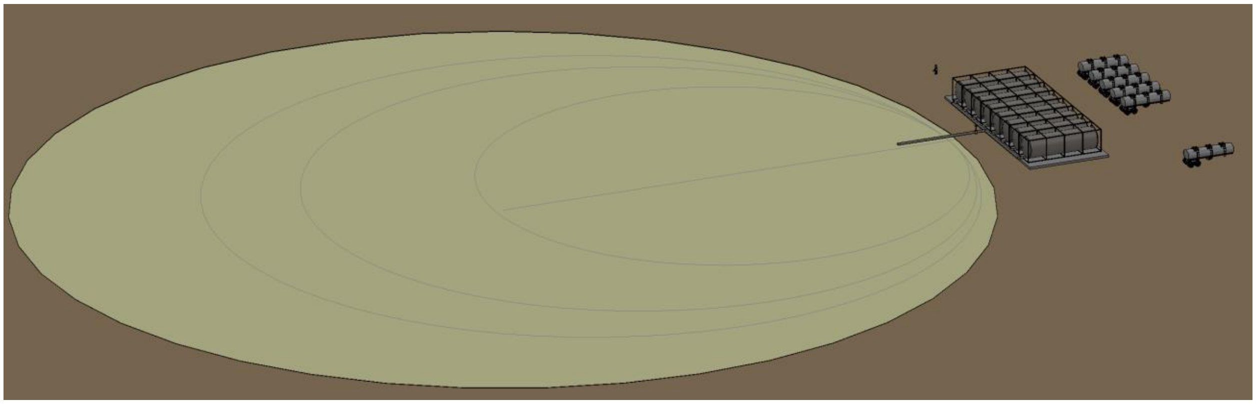

Figure 4. Experimental Setup for Dispersion Testing

The five over the road tankers behind the eight isotainer tanks represent the compressed gas tube trailers and the one tanker by itself represents an offloading 10,000 gal LNG road trailer. Note that the tube trailers would likely be stationed outside the hazard zone, requiring a long pipe to connect them to the tanks.

2.2.3. Dispersion Test Siting

Three potential sites have been identified for the dispersion tests. All three are remote sites that conduct a wide range of hazardous testing that requires large exclusion zones. Sandia and DOE have worked in the past with all three of these groups, and all three have shown interest in fielding the experiments. ROM cost information has been obtained from two of the sites. From our discussions with these sites, all have the ability to construct both wet and dry pools, have water sources for filling the wet pools, and can provide a labor force for construction, security, instrumentation, photography, and testing support. In addition, each facility can provide miscellaneous items such as porta-potties, comfort trailers, generators, lite-all, radios, fuel for generators, etc. NEPA permits (and the Environmental Assessment if required) and approvals are likely. Airfield support for flying assets including fuel can be provided. Also, foreign nationals, within some limits, can be accommodated.

Tonopah Test Range, Nevada

The first site considered is the Tonopah Test Range (TTR). The Tonopah Test Range comprises 280 square miles and has been used by the DOE since the early 1950s. The facility is surrounded on three sides by the Nevada Test and Training Range complex and to the north by the U.S. Bureau of Land Management's open range. The town of Tonopah is located 20 miles northwest of the main gate of the Tonopah Test Range and is approximately 150 miles northwest of Las Vegas, Nevada. Sandia is the facility operator and manager under an Air Force permit with the National Nuclear Security Administration. The test range is used to support the DOE mission in stockpile stewardship, as well as research and design of new weapons and weapon components. The facility offers a unique series of test beds for testing DOE and DoD weapons. The dispersion tests would be sited near Pedro Lake (Coordinates 37.78°N 116.77°W) (see Figure 5).

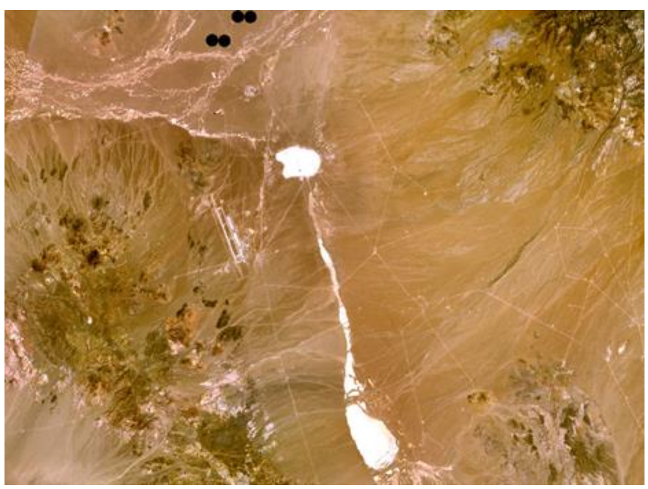

Figure 5. Pedro Lake Test Area at TTR, Nevada

Pedro Lake is one of a series of large, dry lake playas at TTR, shown in white in Figure 5. The lakes beds are 10's of kms wide and long. The surface of these lakes is flat and hard packed clay, a good surrogate for hard soil and concrete spill surfaces and associated dispersions. Since Sandia operates this facility, no additional contracting requirements would be imposed, all work would be coordinated though the same management and ES&H structure.

Frenchman Flats at NNS, Nevada

The second site is the Frenchman Flats area located at the Nevada National Security Site (NNSS). This site is about 60 miles north of Las Vegas, Nevada. The lakebed is primarily hard packed clay at an elevation of 3,080 feet above MSL (see Figure 6). Artificial "lakes" have previously been constructed by building up a berm and flooding the area with well water. The NNSS owns its airspace and has a local ATC station at the NPTEC control building with a common area radar feed from Nellis AFB. Several very large LNG releases on the lakebed have previously been conducted (such as the Falcon LNG dispersion series conducted in 1987 by LLNL).

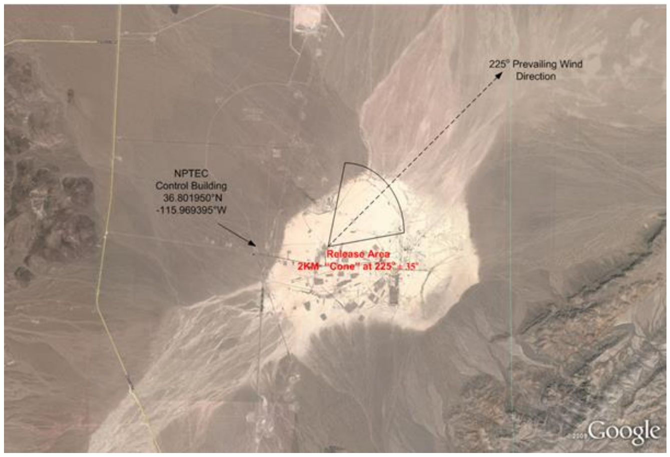

Figure 6. Frenchman Flat Test Area at NNSS, Nevada

White Sands Missile Range, New Mexico

The third site considered is at White Sands Missile Range (WSMR) located near Las Cruces, New Mexico, approximately 60 miles north of El Paso, Texas (Coordinates 32°39’N 106°.18’W) (see Figure 7). White Sands Missile Range (WSMR) is a United States Army rocket range of almost 3,200 square miles (8,300 km^2) in parts of five counties in southern New Mexico. The dry lake playas are hard packed clay similar to the other test sites and have been used in the past for landing of the Space Shuttle.

Figure 7. White Sands Missile Range, New Mexico

2.2.4. Dispersion Test Setup and Instrumentation

This section describes the measurements necessary to meet the experimental data needs.

Note that not all of the instrumentation described below is included in the ROM costs. This additional (or possibly alternate) instrumentation was considered and is presented as an opportunity to consider new state-of-art technology. This instrumentation would be a first time use for data collection at the scales required and therefore will require some feasibility testing in Phase 0 prior to utilizing the technologies in later test phases. However, this advanced instrumentation technology could significantly improve the quality and quantity of data collected.

Meteorological DAQs 20 Towers

Each meteorological tower (placed (TBD) inside the estimated dispersion field) contains a National Instruments chassis with stand-alone cDAQ, to include voltage and thermocouple modules and a wireless card/modem (battery powered). The 10 m tall tower structure contains YM Young instrumentation at 3 stations (1 m, 3 m, and 10 m) (wind speed/direction vane or ultrasonic, pressure and RH/temperature. A soil radiometer is also included.

Methane Concentration DAQs 120 Towers (360 point measurements)

Each methane concentration tower (placed (TBD) inside the estimated dispersion field) contains a National Instruments chassis with stand-alone cDAQ, to include voltage and thermocouple modules and a wireless card/modem (battery powered). Figure 8 shows a proposed 120 tower layout based on equal area.

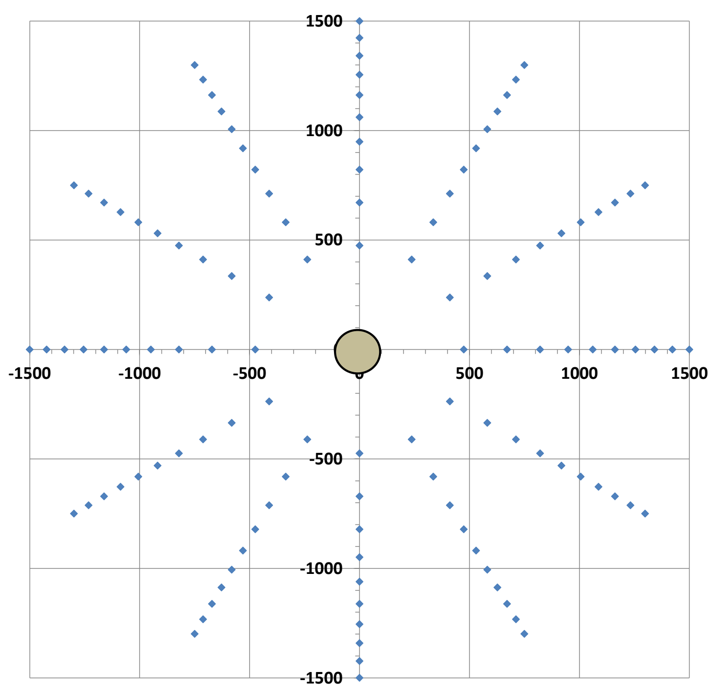

Figure 8. Proposed Methane Tower Layout

Each 10 m tall portable tower structure contains industrial methane concentration instrumentation at 3 heights (1 m, 3 m, and 10 m). This essentially reproduces the successful measurement methodology used by Lawrence Livermore National Laboratories (LLNL) in the 1980's large scale dispersion tests at NTS. The time response of LLNL sensor was 5 Hz. We have looked at reproducing the LLNL sensor since it is likely that today's commercial sensors would have the same issues with ice crystals/fog that LLNL found in the 1980s. Our ROM estimate to reproduce and refine the LLNL instrument using current technology is ~$3000/sensor.

The ROM cost for one methane concentration tower was based on using three commercial industrial sensors with one controller (~$10,700) (CXT-Series SmartWireless® Gas Detectors, see http://detcon.com) and a portable tower (~$2000). This yielded $12,700/tower x 120 towers = ~$1.5M (only hardware cost, labor to assemble and calibrate was costed separately).

The selected methane concentration measurement technique likely has the greatest uncertainty on the dispersion testing cost estimate. Note that this proposal assumes only the point measurements (individual sensor technology) will be used for methane concentration data collection. As such, we believe the -30% and +50% margins are appropriate given the relatively low uncertainty to reproduce the LLNL methodology.

LIDAR for Methane Concentration (optional- not included in ROM costs)

ARES and AURA are Sandia-developed laser remote sensing systems that may be used to produce maps of the methane concentration from the LNG spills over a wide area. These LIDAR-based systems send out short laser pulses and time-resolve the backscattered light to produce a range-resolved measurement of aerosol or molecular concentration. Both LIDARs can scan horizontally and vertically to provide 3-D measurement coverage of the cloud. To map methane concentration, we could measure the Raman-scattered light from the methane cloud and ratio it to the Raman-scattered light from ambient nitrogen in the atmosphere. The Raman cross sections of nitrogen and methane are well known and the ambient nitrogen concentration can be computed using ideal gas law that can provide a simple and reliable calibration. Both LIDAR systems can be operated from a standoff distance of several thousand meters from the LNG spill and are capable of measuring the methane concentration in a cloud several thousand meters in extent. They can be remotely operated via an Ethernet connection to provide additional standoff distance for the safety of the operators.

Ares and AURA have been used on numerous field tests at remote sites in several configurations: in UAVs, airplanes, on top of a scissors lift, and in the back of a dedicated van. The scanning rate of the cloud is set by the user depending upon desired knowledge of the time evolution of the cloud's concentration and measurement precision/accuracy.
Caveats:

- ARES can scan ±45° side to side and ±20° vertically while AURA is limited to ±23.5° side to side and ±8° vertically.
- The sensitivity to measure methane will be greatly improved if the test is performed at night. Alternatively, we could modify the systems to operate at a shorter laser wavelength to move the Raman signal into a spectral region with less solar illumination.

- There will be a tradeoff between spatial resolution, minimum detectable methane concentration, and length of time required to map the region. At low concentration, we may need to integrate more laser shots (time) or integrate a longer path length of cloud (spatial) in order to obtain desired/required sensitivity. Nevertheless, the scanning LIDAR technique should provide an ideal way to produce a 2-D or 3-D map of methane concentration over a very wide area.

Ground-Based Spectroscopy - Neptune, FTIR, 2D Thermal Imaging for Methane Concentration (optional- not included in ROM costs)

Neptune is a Sandia-developed gas correlation imaging technique that could be used in ground-based or airborne-based systems to detect extremely low gas concentrations. Neptune can detect weak infrared signals from a selected gas species (such as methane), with resolutions on the order of centimeters from distances of half a kilometer away. Sunlight is used to calibrate the instrument, which must operate in the daytime since it measures absorption of specific wavelengths of sunlight.

The FTIR is a Sandia-owned Fourier Transform Interferometer manufactured by ABB – Bomem in Québec. The MR304 can be configured with two separate channels, one with a mercury-cadmium-telluride (MCT) detector and the other with an InSb detector. With both channels, the instrument is capable of measuring the spectral region from 1.0 to 15.0 μm with a spectral resolution of up to 1 cm^{-1}. The instrument was used in the Phoenix pool fire test series with the narrow angle telescope to have a field of view (FOV) of 4.9 mrad. The nearest focusing range for the narrow angle telescope is 30 meters and the range for the field collect was over 1 km.

The Sandia-owned thermal imager is a microbolometer based camera that has a broadband response from 8-12 μm. The field-of-view of the instrument is approximately 26º by 19.6º. The camera can output images at a rate of 30 frames per second. A LabView® GUI and data acquisition software application was developed to allow streaming of video straight to hard disc over an IEEE 1394 interface.

Hyperspectral and Thermal Imaging Cameras on Airborne Platform for Methane Concentration (optional- not included in ROM costs)

The Telops Inc. Hyper-Cam is a lightweight and compact hyperspectral-imaging sensor which uses Fourier Transform Infrared (FT-IR) technology. This advanced high-performance spectrometer allows to detect and identify substances either gases or solids from a distance of up to 5 kilometers. It provides real-time chemical imaging as well as spatial and spectral information about the IR targets. The Hyper-Cam can be used as an advanced hyperspectral-imaging solution for airborne infrared spectroscopy to produce hyperspectral maps of the ground surveyed from an airplane. The airborne module includes a stabilization platform, a GPS/INS, an image motion compensation mirror, a navigation module as well as all the necessary airborne operation software.

The HD-IR 1280 is a high definition, cooled, infrared camera, with a resolution of 1280 x 1024 pixels with a frame rate of up to 90 frames per second. This high performance, scientific, infrared imaging camera features real-time processing and real-time calibration algorithms which allows users to obtain temperature calibrated data in real-time. Information on this is available at http://www.telops.com/en/products/hyperspectral-imaging/606-airborne-module

Multispectral Thermal Imager (MTI) for Methane Concentration
(optional - not included in ROM costs)

The Multispectral Thermal Imager (MTI) satellite is a research and development project sponsored by the U.S. Department of Energy. Its primary mission is to demonstrate advanced multispectral and thermal imaging from a satellite, including new technologies, data processing, and analysis techniques and validation by reference to ground truth. The MTI satellite was launched on March 12, 2000 into a 580 km 610 km, sun-synchronous orbit with nominal 1 A.M. and 1 P.M. equatorial crossing times. The satellite-based sensors obtain radiance data (radiometrically calibrated, medium resolution imagery in 15 spectral bands ranging from 0.45 to 10.70 μm) that are subsequently processed into measurements of atmospheric and surface properties such as column water vapor, atmospheric aerosol loading, surface temperatures, material composition, and others.

Storage Tank DAQs (from Fire test, no costs)

Pool DAQs (from Fire test, no costs)

Aerial Video/IR Coverage (10 tests)

The cost for aerial video/IR coverage is primarily the cost for helicopter rental with operators for the ten tests. Cost for additional camera rentals and calibration is not included.

Meteorological Support

Meteorological data (wind direction and velocity, temperature, relative humidity and barometric pressure) could be measured and recorded with portable instruments fielded by the Meteorological Monitoring Program at Sandia (SODAR and large LNG tower). Support would also include analysis and prediction of atmospheric conditions at the remote site to determine optimal test times.

Photometric Cameras (from Fire test, co costs)

Storage Tank Procurement (from Fire test, no costs)

Storage Tank Install

This would be similar to the pool fires tests, with the exception of the prefabricated cover that would be dismantled and assembled at the dispersion test site.

Remote Site Support

This support includes constructing the dispersion pools, equipment rentals, construction of pipelines and culvert to supply water to the water dispersion pools, general labor, security, communications, instrumentation, photography, and testing support, and miscellaneous facility charges (i.e., porta-potties, comfort trailers, generators, lite-all, radios, fuel for generators, etc.). This also include the NEPA (and EA if necessary) costs and airfield support for flying assets.

2.2.5. Dispersion Testing Cost Elements

Table 6 summarizes the cost estimates for materials, purchases and subcontracts for services for performing the proposed ten GDF LNG dispersion tests on both land and water.

Table 6. ROM Hardware/Purchases/Subcontracts Cost Estimate for Siting Dispersion Tests

Dispersion - Hardware/Purchases/Subcontracts for Services	**Cost ($US)**
Meteorological DAQs 20 Towers	$594,000
Methane Concentration DAQs 120 Towers	$2,818,000
Storage Tank DAQs (from Fire tests)	$0
Pool DAQs (from Fire tests)	$0
Aerial Video/IR Coverage (10 tests)	$155,000
Meteorological Support	$50,000
Photometric Cameras (from Fire tests)	$0
Storage Tank (ship from Fire tests)	$321,000
Remote Site Construction and Test Support	$2,990,000
LNG procurement for dispersion tests	$1,624,000
Total	**$8,552,000**

Table 9 in Section 5 provides the summary cost estimate for both the pool fire and the dispersions testing. That summary cost estimate includes direct Sandia labor, overhead, and required taxes for detailed test planning and cost estimation, work project agreements, work planning and controls to meet environmental safety and health requirements, permits, pretest analysis and modeling, project management including travel, data acquisition programming, instrumentation calibration, and experimental setup at both the Phoenix test site and the remote test site. Labor estimates for Sandia technical and technician support for the dispersion tests assumes the support for ten tests at ten days/test and posttest data analysis and reports.

2.2.6. Dispersion Testing Safety and Engineered Safety Considerations

As mentioned above, the small dispersion tests could be conducted at Sandia’s Albuquerque site where the large LNG pool fire tests are conducted. This location has been specifically designed for the testing of hazardous materials. As such there are significant operational safety controls in place in this test area. However, additional testing safety controls for dispersion will be determined through CFD simulations and safety basis calculations. For the large dispersion tests, all three large testing areas identified are extremely remote and two have previously conducted cryogenic gas dispersion tests.

The LNG dispersion tests will require the development of engineered safety measures to address a range of potential hazards including fires, storage system integrity, thermal (cryogenic to fire) hazards, asphyxiation, explosion, and aviation operations (helicopter and airport traffic). Engineered safety measures and safe operating plans will be developed in collaboration with GDF safety representatives and Sandia ES&H representatives to address all safety issues and challenges identified during the final planning and design phases for all equipment protection, operational safety, and personnel safety. Those engineered safety measures will undergo a through safety review before testing operations are conducted. The program design and construction schedule allows for the comprehensive evaluation of all safety and engineered safety systems and operations prior to testing.

3. PROPOSED SANDIA LNG PROCUREMENT APPROACH

The Phoenix large-scale LNG spill tests were performed with liquid methane (>99.5%) as a surrogate for Liquified Natural Gas (LNG) which can have a wide range in composition (depending on the source), from almost pure methane to mixtures composed primarily of methane (typically, at least 90 percent) but also containing ethane, propane and heavier hydrocarbons and small quantities of nitrogen, oxygen, carbon dioxide, sulfur compounds, and water. The purpose of using a pure grade was two-fold: 1) minimize the potential for explosive rapid phase transitions (RPTs) that could damage or destroy the experimental setup and 2) minimize the parameter variations to reduce uncertainty in the analysis of the test data and for the use of present and future model development and validation. Note that previous historic experiments using typical LNG have shown that the methane burns off first, with little participation by the heavier hydrocarbons until late in the test.

Two suppliers were contacted for interest and ROM estimates for the supply of ~2.4 million gallons of LNG via 10,000 gallon road trailers (note this is ~240 trips). Both suppliers have the capability and have expressed interest in bidding on the fuel contract.

The first supplier is Applied Natural Gas Fuels, Inc. (Corporate Headquarters Westlake Village, CA). Applied's LNG Plant in Topock, Arizona has a capacity of 172,000 gallons per day. In addition, Applied recently announced a plan to build up to five liquefiers near the Dallas, Texas area. Each liquefier will have a production capacity of 86,000 gallons of LNG per day, with total on-site storage to eventually reach 1.5 million gallons of LNG. The first plant is expected to be operational in mid-2015. The methane content of LNG produced at the liquefaction plants in Topock, AZ are guaranteed to be a minimum of 97% methane and could be as high as 99.3% (if requested). The cost per LNG gallon (in $/LNG gallon) is based on the formula: ((SoCal Index/12.1) x 1.2) + $0.50 = cost per LNG gallon + applicable taxes & transportation.

The October 2013 example calculation: (($3.53/12.1) x 1.2) + $0.50 = $0.8501 + applicable taxes & transportation. Transportation to Tonopah, NV is approximately 335 miles, yielding a transport cost of about $1900 per round trip or about $0.19 per LNG gallon. Transportation to Albuquerque, NM is approximately 525 miles, yielding a transport cost of about $3,000 per round trip or about $0.30 per LNG gallon. Therefore the total cost/per gallon ranges between $1.04 to $1.15 per LNG gallon delivered + applicable taxes.

The second supplier is Clean Energy (Corporate Headquarters Newport Beach, CA). Clean Energy’s Pickens Plant (located in Willis, Texas, approximately 60 miles north of Houston) can produce up to 100,000 gallons of vehicle-grade LNG per day, includes truck loading facilities and an 800,000-gallon storage tank. The Clean Energy LNG Plant in Boron, California was built to produce up to 160,000 gallons of LNG per day, and was designed to be upgraded to produce up to 240,000 gallons of LNG per day. The plant has a 1.5-million-gallon LNG storage tank. The methane concentration from the Pickens’s plant is >99.8%. The Boron plant produces LNG with 98.8% methane, 0.93% ethane, and 0.27% nitrogen. Clean Energy’s costs are comparable to the costs provided by Applied.

4. PROPOSED SANDIA WAVE IMPACT TESTING APPROACH

Sandia proposes the use of SNL/Albuquerque Water Impact Facility (WIF) as the site for the wave effect study. Free spillage of liquid nitrogen (LN_2) would be used as a safe surrogate for LNG (due to the close proximity of inhabited building) and the WIF would be modified to produce controllable and repeatable waves at relevant scales. WIF has previously been used for a number of LNG studies.

Figure 9 shows small-scale pool fire testing using a 10,000 gallon road trailer and insulated pipeline extending to the center of the WIF lake. The existing WIF tank basin, 188 ft. x 120 ft. x 50 ft. deep (57 m x 37 m x 15 m), is essentially an upside-down, truncated pyramid whose depth varies from zero around the tank perimeter to a maximum of 50 ft.

Figure 9. LNG Free Spillage Pool Fire Testing at WIF

Unrelated to this proposal, a detailed 2010 engineering design report studied necessary modifications to the WIF to provide waves for the testing of scale models of ocean energy generating devices. Figure 10 shows the conceptual wave generation system and tank drawings resulting from that study.

Due to the translating nature of waves, each wave must be effectively quelled at the end opposite the wave generator such that there is no reflection. Experience combined with research in the literature recommends a full wavelength worth of dampening for the best results. These two factors combined mean the wavelength generated should not exceed half the tank length. The wave period corresponding to this maximum wavelength is approximately 4.5 seconds.

The following represents the final 2010 report design parameters for generating repeatable waves for the WIF:

- Maximum Wave Height: 1.5 m
- Wave Period: 2.0 to 4.5 seconds
- Wave Type: Linear, Stokes, Translating
- Wave Pattern: Continuous

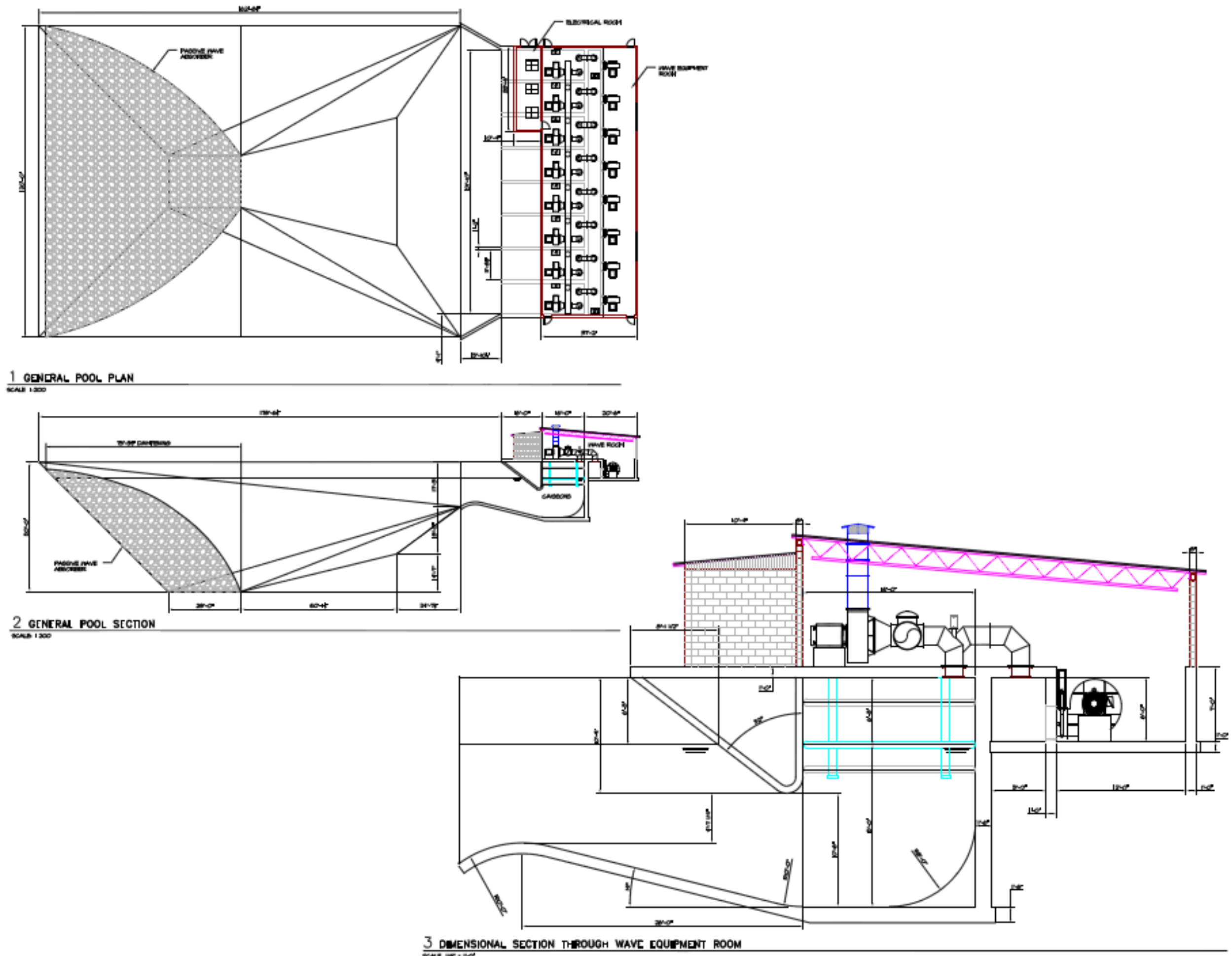

Figure 10. Conceptual Wave Generation System & Tank Drawings

Table 7 presents the cost and schedule summary from the 2010 engineering study for the wave energy generating equipment as a function of desired wave height. It is likely that the wave height needed for the spill testing is on the order of 0.5 m or less. This would reduce the equipment mechanical power by a factor of 4, and reduce total wave system cost to ~$4 M. The energy needs for this type system would not exceed the current power availability, which will help reduce implementation costs.

Table 7. Cost and schedule summary for wave generating capability at WIF

Wave Generating Capability	Power Required	Total System Cost	Completion Schedule
0.9 m wave height	1.4 MW*	$5.1 M	1.5 years
1.1 m wave height	2MW	$6.9 M	1.5 years
1.5 m wave height	4MW	$7.6 M	1.5 years

*Existing power at WIF

As part of the DOE/USCG LNG Vessel Cascading Damage Structural and Thermal Analyses study in 2008, Sandia contracted with Adaptive Research to add a cryogenic liquid evaporation model to the their multiphase computational fluid dynamics (CFD) code CFD2000. Use of these available models and simulations could be used in conjunction with the experiments to help analyze the spill data and validate the wave impact models. Figure 11 shows a simulated spill from a breached membrane ship from that study and flow interaction modeling work.

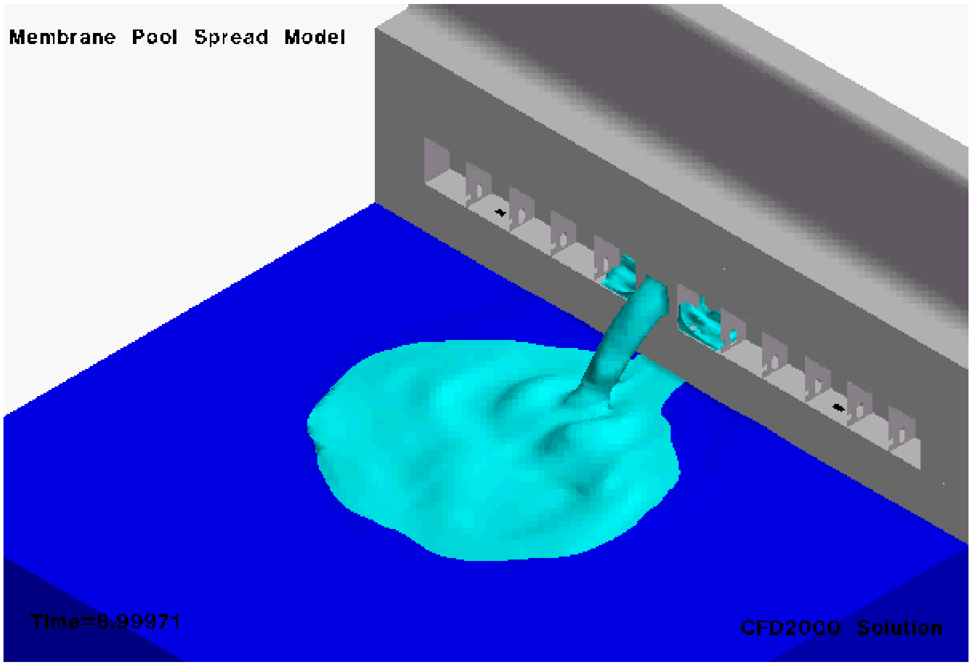

Figure 11. Simulated LNG Spill on Water using Free Surface CFD Code

Proposed instrumentation would consist mainly of measuring the LN_2 discharge rate and thermocouples and cameras (video and thermal imaging) to monitor liquid spread and the cold nitrogen gas cloud dispersion.

Table 8 summarizes the cost estimates for materials, purchases and subcontracts for services for performing the LN_2 spillage tests with waves at the WIF. Because this test program would be one of the first detailed test series of wave impacts on liquefied gas spills and dispersions, this is no previous tests to help guide in the test development or analysis development. Due to the separate infrastructure required we have broken the costs out separately.

Table 10 in Section 5 provides the summary cost estimate for the wave effects study. The summary cost estimate includes Sandia labor, overhead, and required taxes for detailed test planning and cost estimation, work project agreements, work planning and controls to meet environmental safety and health requirements, permits, pretest analysis and modeling, project management including travel, data acquisition programming, instrumentation calibration, and experimental setup at the WIF. Labor estimates for the wave effects study assumes support for twelve tests at one day/test and posttest data analysis and reports.

Table 8. ROM Hardware/Purchases/Subcontracts for Services for Wave Impact Study

Wave Study - Hardware/Purchases/Subcontracts for Services	Cost ($US)
Facility Site Work	$4,000
Purchase/install wave machine	$4,800,000
Cryogenic pipeline / process equipment	$42,000
Test instrumentation	$77,000
Cryogenic LN2 tank lease (1 yr.)	$62,000
Total Costs	**$4,985,000**

5. PROPOSED SANDIA BUDGET AND SCHEDULE

This section summarizes the budget and schedule for the Sandia proposed testing and analysis efforts to conduct the requested GDF LNG spill program. It breaks the costs and schedule into two parts, the pool fire and dispersion test efforts, and the wave impact test efforts. The wave impact testing is broken out separately due to the requirement of different infrastructure.

5.1. Cost Summary

5.1.1. LNG Pool Fire and Dispersion Study

The cost summary for the LNG pool fire and dispersion project is presented in Table 9. The methodology and the associated management oversight provided ensure that the costs of the construction and testing identified in the proposal can be performed within a -30% to + 50% range of the actual costs.

Table 9. GDF LNG Tests Cost Estimate Summary

Cost Estimate - Summary

Prepared For:

Project Name: GDF Suez LNG Test #2 11-20-13

Managing Org: 01532

Period of Performance: 1/1/2014 (Begin Date) to 1/1/2018 (End Date)

Cost Elements	FY2014	FY2015	FY2016	FY2017	Total
Labor	$1,472,371	$664,092	$2,006,283	$2,679,011	$6,821,757
Materials & Purchases	$0	$5,672,680	$5,216,100	$1,629,172	$12,517,952
Subcontracts (for services)	$0	$1,422,415	$1,765,812	$986,393	$4,174,620
Travel	$59,307	$0	$64,963	$321,257	$445,527
Other Direct Costs	$46,475	$523,245	$577,481	$306,792	$1,453,993
Contingency	$0	$0	$0	$0	$0
Estimated Sandia Project Cost*	$1,578,152	$8,282,433	$9,630,638	$5,922,625	$25,413,848
Fed. Adm. Charge - if applicable	$47,345	$248,473	$288,919	$177,679	$762,415
Estimated Total Project Cost	$1,625,497	$8,530,906	$9,919,557	$6,100,303	$26,176,263
Continuity Funding - if required	$0	$0	$0	$0	$0
Total Required Funding	$1,625,497	$8,530,906	$9,919,557	$6,100,303	$26,176,263

* Excludes carryover funding

Rough Order of Magnitude (ROM)

Contained herein is a Rough Order of Magnitude (ROM) cost estimate that has been provided to enable initial planning for this proposed project. This ROM cost estimate is submitted to facilitate informal discussions in relation to this project and is NOT intended to commit Sandia National Laboratories (SNL) or its resources.

Furthermore, as a Federally Funded Research and Development Center (FFRDC), SNL must be compliant with the Anti-Deficiency Act and operate on a full cost recovery basis. Therefore, while Sandia, in conjunction with the Sponsor, will use best judgment to execute work and to address the highest risks and most important issues in order to effectively manage within cost constraints, this ROM estimate and any subsequent approved cost estimates are on a "full-cost recovery" basis. Thus, work can neither commence nor continue unless adequate funding has been accepted and certified by DOE.

Note that the ROM cost estimate includes only the selected key instrumentation described previously. The cost of the instrumentation to measure methane concentrations during the dispersion tests is the greatest challenge. It is believed possible to resurrect the traditional point measurements, but the proposed scale of the largest releases requires unprecedented numbers of sensors and ultimately could yield low resolution. New state-of-the-art non-invasive optical techniques for measuring large-scale releases of gases have made tremendous strides in the twenty-five years since some of the initial LNG dispersion tests were performed. However, due to the uncertainty of using these new methods at the proposed scales and the estimated costs (order $1-2 M for each), the ROM estimate includes costs for only the point sensor measurements.

The LNG pool fire and dispersion cost summary does not include the potential recoverable hardware costs on the order of $6 M. The hardware, which is considered GDF property, includes the meteorological and methane concentration towers, instrumentation, and DAQs, some cameras, and the eight large modular LNG tanks. It is assumed GDF would possibly want to use this equipment in their future experimental work. The total project costs would then be reduced to ~$20 M if the cost recovery of hardware is included. If these elements were purchased by GDF and provided to Sandia, additional cost savings might also occur. In a final cost analysis, these opportunities should be considered relative to the overall costs and benefits.

5.1.2. Wave Impact Study

The cost summary for the wave impacts study testing is presented in Table 10. The methodology and the associated management oversight provided ensure that the costs of the construction and testing identified in the proposal can be performed within a -30% to + 50% range of the actual costs.

The need for reproducible waves was a big driver in the proposed approach for this testing. Since there is no available test data, reproducible waves are needed to develop a good database for estimating impacts and to validate models. This requires a controlled approach which unfortunately can be expensive. The DOE has wrestled with this same issue in their ocean energy program. Obtaining validation data pertaining to new technologies in the open ocean is difficult, since natural waves vary continuously and are impacted more by weather conditions and sea conditions outside the control of the researcher. Validating analysis models without having sufficient quality information on the actual input parameters is extremely difficult if not impossible. Therefore, a less ambitious research program involving smaller scale tests might be a better consideration.

Table 10. GDF Wave Impact Study Cost Estimate Summary

Cost Estimate - Summary

Prepared For:

Project Name: GDF Wave Effect Study

Managing Org: 01532

Period of Performance: 1/1/2014 (Begin Date) to 1/1/2017 (End Date)

Cost Elements	FY2014	FY2015	FY2016	Total
Labor	$292,357	$303,662	$310,310	$906,329
Materials & Purchases	$2,502,755	$2,521,851	$0	$5,024,606
Other Direct Costs	$189,794	$191,400	$11,989	$393,184
Contingency	$0	$0	$0	$0
Estimated Sandia Project Cost*	$2,984,907	$3,016,913	$322,299	$6,324,119
Fed. Adm. Charge - if applicable	$89,547	$90,507	$9,669	$189,724
Estimated Total Project Cost	$3,074,454	$3,107,421	$331,968	$6,513,842
Continuity Funding - if required	$0	$0	$0	$0
Total Required Funding	$3,074,454	$3,107,421	$331,968	$6,513,842

* Excludes carryover funding

Rough Order of Magnitude (ROM)

Contained herein is a Rough Order of Magnitude (ROM) cost estimate that has been provided to enable initial planning for this proposed project. This ROM cost estimate is submitted to facilitate informal discussions in relation to this project and is NOT intended to commit Sandia National Laboratories (SNL) or its resources.

Furthermore, as a Federally Funded Research and Development Center (FFRDC), SNL must be compliant with the Anti-Deficiency Act and operate on a full cost recovery basis. Therefore, while Sandia, in conjunction with the Sponsor, will use best judgment to execute work and to address the highest risks and most important issues in order to effectively manage within cost constraints, this ROM estimate and any subsequent approved cost estimates are on a "full-cost recovery" basis. Thus, work can neither commence nor continue unless adequate funding has been accepted and certified by DOE.

5.2. Schedule Summary

5.2.1. LNG Pool Fire and Dispersion Study

Sandia has provided a ROM cost estimate, a coarse cost estimate and site(s) identification. If accepted, the next phase would commence and include detailed test program planning (sharing partners' goals and final test program definition), detailed cost estimates, project planning, value engineering, test and hardware design, and contractual agreements. This phase is anticipated to be a 9-12 month effort that would end in December 2014. The next phase would then commence in 2015 to include test site construction and/or modification, experimental testing and measurements, data processing, and final reports. This phase is anticipated to be a 27-30 month effort, ending in 2017.

5.2.2. Wave Impact Study

Construction of the wave generator at the WIF is estimated to be an 18 month effort that would end in June 2015. Experimental tests and measurements, data processing, and final reports are expected to be a 12 month effort that would end in June 2016.

5.3. Project and Cost Management

Mike Hightower will be the designated Project Manager and principal point of contact for this program. Tom Blanchat will be the Principal Investigator, coordinating overall test design, testing, and data analysis and reporting. Carlos Lopez will be a key contributor, leading thermal and systems analyses and test and management support. Anay Luketa will also be a key contributor, leading safety and design analyses and modeling efforts. Short biographies for these key participants are provided in Attachment A. The overall staff and assignments are subject to change at the discretion of the project manager.

Sandia will provide budgetary control of the project and will provide details of expended and predicted cost profiles for the duration of the contract. Costs will be reported on an agreed upon frequency basis.

5.4. Consulting and Peer Review

It is highly recommended that knowledgeable consultants be included in the project. We have contacted Dr. Ron Koopman (retired LLNL) who was the principal investigator for dispersion and pool fires at China Lake NWC and NTS in the 1980's, he is available and willing to participate. We have also contacted John Gibson (Cryogenics International) who advised Sandia in the fabrication of piping and procuring storage tanks and was who was instrumental in the success of the Sandia LNG tests.

Finally, an independent panel of experts who would provide peer review and participate in all stages from planning to final results will be a key to ensuring proper test design, test execution, and data quality of the work.

ATTACHMENT A: SELECTED PARTICIPATING BIOGRAPHIES

Mike Hightower
Mr. Hightower is a Distinguished Member of the Technical Staff in the Energy Technologies and Systems Solutions Center at Sandia National Laboratories in Albuquerque, New Mexico. He is a civil and environmental engineer with over 30 years of experience in research and development. His current efforts include research and evaluation of innovative environmental and energy technologies and the reliability, security, and protection of critical water and energy infrastructures. One of his current major roles is as a project leader on energy and water interdependencies research for the U.S. He helped develop a Report to Congress on the interdependencies of these two infrastructures and has helped the DOE, the National Research Council, and the National Science Foundation develop Science and Technology Research programs in this area. Another major role has been as program manager of Sandia's LNG research programs for the past 10 years. This has included leading a number of major national and international studies of LNG safety during marine transport, and most recently in coordinating a large test program, developing a series of technical reports, and writing a Report to Congress on LNG ship damage and public hazards from very large LNG spills over water. Mike holds Bachelor's and Master's degrees in civil engineering from New Mexico State University. He is past-Chair of ASME's Environmental Engineering Division and leads ASME's Interdisciplinary Council on Energy and Water Issues.

Tom Blanchat
Dr. Blanchat is a Principal Member of the Technical Staff in the Fire Science & Technology Department at Sandia National Laboratories in Albuquerque, NM. He is a nuclear engineer with over 30 years of experience in large-scale experimental research and development. His fields of specialization include nuclear reactor systems and systems modeling, computational and experimental fluid mechanics and heat transfer, two-phase fluid flow visualization using optical imaging techniques and severe accident testing. Tom has been the principal investigator for all LNG fuel fire experimental research programs performed for the DoD, DOE, and industry customers at Sandia National Laboratories. Tom holds Bachelor's, Master's, and Doctorate degrees in nuclear engineering from Texas A&M University.

Anay Luketa
Dr. Anay Luketa is currently a Principal Member of Technical Staff at Sandia National Laboratories in the Fire Science and Technology Department. She received a Doctor of Philosophy in Mechanical Engineering at the University of Washington. Her work pertaining to LNG includes conducting blast, dispersion, and pool fire calculations using integral and CFD models. She is a major author of the Sandia LNG report released in 2004 and of the 2008 Sandia report for the larger class of LNG carriers. She has also conducted a comprehensive review of experiments and modeling of LNG dispersion and fire and has provided guidance for several U.S. deep water LNG ports, assisting the United States Coast Guard, and conducted a hazard assessment for an international deep water port in Hadera, Israel.

Carlos Lopez
Mr. Lopez is a Principal Member of the Technical Staff in the Nuclear Energy and Fuel Cycle Center at Sandia National Laboratories. He has 16 years of experience performing fire and thermal testing and analysis at Sandia. Mr. Lopez holds a Bachelor of Science in Mechanical Engineering from the University of Turabo in Puerto Rico and a Master of Science in Mechanical Engineering from the University of New Mexico. He is the Thermal Lead for the Structural and Thermal Analysis Department at Sandia and has been involved in numerous field tests and high-end computer analyses of systems exposed to severe accident conditions for research, risk studies, and certification. On the LNG Cascading Damage Study, Carlos was the lead for all thermal and flow testing and analysis aspects of the project.

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