U.S. DEPARTMENT OF TRANSPORTATION

PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION

FINAL ENVIRONMENTAL ASSESSMENT

Phast version 8.4

Contents

A. Introduction

The National Environmental Policy Act (NEPA), 42 United States Code (USC) 321 – 4375, Council on Environmental Quality regulations, 40 Code of Federal Regulations (C.F.R. or CFR) 1500-1508, and U.S. Department of Transportation (DOT) Order 5610.1C, requires the Pipeline and Hazardous Materials Safety Administration (PHMSA) Office of Pipeline Safety (OPS) to analyze a proposed action to determine whether the implementation of such action would have a significant impact on the human environment. PHMSA is analyzing this petition submitted by DNV for approval of Phast version 8.4 (Phast 8.4) for use as an alternate model for LNG dispersion exclusion zone, pursuant to the standard set out in 49 CFR § 193.2059, including the potential risks to public safety and the environment that could result from our decision to grant or deny the request. In addition to the evaluation of the physical factors of Phast 8.4 and associated validation data, PHMSA also has analyzed Phast 8.4 results in comparison with the current approved alternate model (i.e., Phast 6.7). In this final environmental assessment (FEA), PHMSA finds that its approval of the use of the Phast 8.4 under 49 CFR §§ 190.9 and 193.2059(a) will not have a significant impact on the human environment.

DNV is a provider of digital solutions and software applications with focus on the energy, maritime, and healthcare markets. DNV's digital solutions are used to manage risk and performance for pipelines, processing plants, and other facilities. DNV's other services include the maritime industry, energy value chain, and business assurance.

The accompanying documents are available at https://www.regulations.gov/docket/PHMSA-2021-0041

B. Model Description

- ### Background

Title 49 CFR 193 prescribes the federal safety standards for liquefied natural gas (LNG) facilities, and regulation § 193.2059(a) prescribes the hazard modeling tools to determine an exclusion zone around LNG containers and LNG transfer systems. The regulation states:

> *"Flammable vapor-gas dispersion distances must be determined in accordance with the model described in the GTI-04/0049, "LNG Vapor Dispersion Prediction with the DEGADIS 2.1 Dense Gas Dispersion Model"" (incorporated by reference, see § 193.2013)." Alternatively, in order to account for additional cloud dilution which may be caused by the complex flow patterns induced by tank and dike structure, dispersion distances may be calculated in accordance with the model described in the Gas Research Institute report GRI-96/0396.5 (incorporated by reference, see § 193.2013), "Evaluation of Mitigation Methods for Accidental LNG Releases. Volume 5: Using FEM3A for LNG Accident Consequence Analyses". The use of alternate models which take into account the same physical factors and have been validated by experimental test data shall be permitted, subject to the Administrator's approval."*

DNV's Phast 6.7 software package was previously approved by PHMSA in October 2011 as an alternate model permitted to assess flammable vapor dispersion exclusion zones as outlined in § 193.2059(a). On September 4, 2020, DNV submitted a petition requesting approval of the updated version Phast 8.4 for such LNG facility assessments (Docket No. PHMSA-2021-0041 at www.regulations.gov). DNV provided multiple versions of the summary reports, sensitivity simulation results and sensitivity reports, change-log reports, and an LNG model validation database. PHSMA has reviewed the reports and validation database provided by DNV. Additionally, PHMSA evaluated the suitability of Phast 8.4 using the three-stage process described in Model Evaluation Protocol 2016 (MEP 2016).[1] Appendix A discusses PHMSA's evaluation process.

- Phast 8.4 and the UDM Capability and Limitations

Phast 8.4 uses its dispersion model (unified dispersion model, UDM) to assess the evolution of a vapor cloud following a release or spill. The UDM is an integral dispersion model that models three different stages in the evolution of a cloud: momentum jet, heavy gas, and passive. The core dispersion model is comprised of a set of differential-algebraic equations (DAEs) solved simultaneously for quantities including cloud mass, horizontal and vertical momentum, horizontal and vertical position, cloud width, mass centroid height and others. The exact model equations vary throughout the cloud's evolution.

The UDM can model "continuous" and "instantaneous" releases. The former includes finite duration and time-varying scenarios. The continuous model assumes all time derivatives are zero (i.e. it predicts a steady state solution). The core UDM model assumes an ellipse shaped top-hat profile, and on this is imposed a similarity profile that allows anything from a top-hat (typically near-field) to a more diffuse Gaussian form (far-field).

For two-phase releases, liquid is assumed to form droplets with a single representative size and trajectory, and additional equations are solved for these. Rainout can occur, as can re-evaporation of the pool into the cloud via a linked pool spreading and vaporization model. The model is suitable for assessing downwind unobstructed dispersion distances. The limitations on the use of the new model are similar to those stipulated for Phast 6.7 [https://www.regulations.gov/document/PHMSA-2011-0075-0025]. Phast may not be appropriate for dispersion:

- From irregularly shaped LNG pools (in particular those with high aspect ratios);
- Involving multiple co-incident releases;
- Over undulating terrain; and/or
- In and around large obstructions or complex geometries.

[1] Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities - Second Edition (Ivings et al., 2016) and Validation Database for Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities: Guide to the LNG Model Evaluation Database, Version 12 (Stewart et al., 2016) (available at www.nfpa.org).

- Changes Since 6.7

  The primary changes from Phast version 6.7 include:

  - *Pools and Pool-cloud linking* – A new model has been introduced that better handles the transfer of mass evaporating from a pool into a vapor cloud. The size, shape, and evolution of the vapor cloud above the pool will be more realistic (e.g., the cloud starts at the upwind edge of the pool rather than its center).

  - *Along-wind diffusion (AWD)* – Releases that are relatively short in duration produce clouds that spread out in all directions, including the primary along-wind direction of travel. Phast 8.4 includes the ability to model this along-wind spreading, while Phast 6.7 could only predict spreading in the 'crosswind' direction (i.e., perpendicular to the wind direction).

  - *Instantaneous expansion (INEX)* – This is a new model for 'catastrophic' loss of containment events (i.e., where the entire inventory of a pressurized vessel or storage tank is released instantaneously). The changes are significant for pressurized liquid releases, but not otherwise.

  The improved modeling of pools and the introduction of AWD are expected to be of most importance for LNG release scenarios and most likely to impact vapor dispersion results when comparing to the previously approved Phast 6.7.

- Types of LNG Facilities Affected

  In accordance with 49 CFR § 193.2051, each LNG facility designed, constructed, replaced, relocated, or significantly altered after March 31, 2000 must be provided with siting requirements of 49 CFR Part 193 and NFPA 59A. As authorized by PHMSA, Phast 8.4 will be available for use in the assessment of new or significantly modified LNG export projects, peak-shaving facilities, and any LNG facilities subject to Part 193.

C. Purpose and Need

Phast is a commercially available product with both software and underlying physical models under continuous development and improvement. Significant changes to both have occurred since Phast 6.7 was approved by PHMSA in 2011. Phast 6.7 was developed using older software technology and may not be installed on modern Windows platforms (i.e., Windows 10 and 11). In addition, old versions of Windows are no longer supported by Microsoft. Thus, users of Phast 6.7 must maintain legacy systems and implement special measures to protect against security breaches. The dispersion model in Phast 6.7 has been superseded by later versions of Phast. The old model is no longer updated or widely used, and support provided by DNV is therefore harder to deliver due to the gradual turnover of frontline staff.

- Benefits

DNV is currently maintaining Phast 6.7 for legacy users with the purpose of demonstrating compliance with the siting requirements in 49 CFR Part 193. With the approval of Phast 8.4, DNV plans to discontinue support Phast 6.7. Approval of Phast 8.4 alleviates the burden for both DNV staff and legacy Phast users from supporting and training for an outdated Phast version. Additionally, the update will improve consistency of results for users who currently maintain two separate Phast versions, and allow easier installation and licensing on modern IT systems. This approval will also improve performance by providing users with access to state-of-the art models and capabilities in Phast 8.4 (for example the *Instantaneous expansion* spill scenario which was not included in 6.7).

The most significant change for this update related to LNG vapor dispersion is the pools and pool-cloud linking for LNG spills that accumulate on the ground and the subsequent vaporization of the liquid pool. The way models handle this interaction between pool and overlying vapor cloud is critical for LNG. Phast 8.4 better predicts the evaporation rate of methane from pools (in general it is lower than in Phast 6.7). The size and shape of the vapor cloud close to the pool will be more realistic, but it will not significantly affect the extent of the predicted flammable region overall.

Another significant change in the model, but less important to the purpose of modeling LNG vapor dispersion, includes the AWD for short duration releases that produces clouds that spread out in all directions. Phast 6.7 could not model this behavior for spills of LNG or other materials, as it could only predict spreading in the crosswind direction. For very large or very short-lasting releases, there can be a noticeable reduction in the size of flammable clouds. The release duration typically lasts for at least 10 minutes in accordance with § 193.2059(c).[2] A release scenario could be of shorter duration with acceptable surveillance and shutdown provisions or when the available system inventory is depleted in less than 10 minutes. Even in the rare scenarios of short-lasting releases, AWD will not significantly affect the results of the flammable vapor cloud. The effect of any along-wind spreading increases with distance from the release point and will be most significant when the cloud is resolved down to part-per-million concentration levels, which is well below the flammable limit for methane to ignite. For the vapor dispersion exclusion zone calculation, the average gas concentration of the vapor cloud in the air must be 2.5 percent in accordance with § 193.2059(b)(1). Therefore, the updates to the AWD feature will not significantly impact the results of vapor dispersion exclusion zones modeled to this comparatively high concentration (i.e., 2.5 percent endpoint comparing to part-per-million concentration levels). At the flammable region, processes other than AWD will tend to dominate the cloud response.

[2] § 193.2059(c) incorporates by reference the section 2.2.3.5 of National Fire Protection Association (NFPA) standard 59A, "Standard for the Production, Storage, and Handling of Liquefied Natural Gas" (2001 edition) for determining design spill.

A detailed description of all of the changes and their implications is provided in the "Phast v8.4 Change-Log Report," which forms part of the petition.[3]

D. Alternatives

- Alternative 1: Petition is denied

  If PHMSA were to deny DNV's petition, Phast 6.7 would need to remain in operation when used to assess a proposed LNG facility's compliance with siting regulations in Part 193, Subpart B. Phast users would be required to maintain legacy systems and require support to accommodate version 6.7. First and foremost, the models used in Phast 6.7 would become increasingly out-of-date in addition to the increased burden to both DNV and Phast users as computers and operating systems are being updated.

  From an operational perspective, while it may remain inconvenient to use Phast 6.7, the time delays in comparison to facility construction timescales are expected to be small. No predicted changes to construction plans would be anticipated.

- Alternative 2: Petition is approved

  PHMSA's approval of Phast 8.4 authorizes the use of the modeling features added after the approval of Phast 6.7, as outlined in Section **Error! Reference source not found.**. In the case of LNG dispersion, the pool-cloud linking and along-wind diffusion features included in 8.4 are of particular relevance.

  The limitations on the use of the new model are similar to those stipulated for Phast 6.7 [https://www.regulations.gov/document/PHMSA-2011-0075-0025]. That is, Phast may not be appropriate for dispersion:

  1. From irregularly shaped LNG pools (in particular those with high aspect ratios);
  2. Involving multiple co-incident releases;
  3. Over undulating terrain; and/or
  4. In and around large obstructions or complex geometries.

  While the new model can predict different hazard distances and therefore impact decisions on site safety, there are no specific environmental or safety impacts of adopting the new model.

E. Affected Resources and Environmental Consequences

- Safety

  LNG is transferred and stored near its boiling point (i.e., approximately minus 260 degrees Fahrenheit) where a loss of containment would result in releases of the cryogenic liquid that would evaporate into its vapor state at ambient temperatures. Contact with the vapor cloud can

[3] Documentations associated with petition can be found at https://www.regulations.gov/docket/PHMSA-2021-0041

cause burns and tissue damage due to cold temperatures and also asphyxiation. In addition, the natural gas vapor cloud (methane) is flammable when the methane-air mixture contains 5 to 15 percent methane. If ignited, a methane vapor cloud may cause injury or death in the affected area. Eventually, the vapor cloud mixes with air and dissipates below its lower flammable limit (i.e., 5 percent methane-air ratio) and it can no longer ignite. Methane is not toxic, and safety impacts would be restricted to contact damage, radiant heat from the fire, and overpressure or blast wave from an explosion of the vapor cloud.

Section 193.2059 requires that LNG facilities define a flammable vapor dispersion exclusion zone to determine the maximum extent to which ignitable clouds of methane may extend and therefore, where an operator or government agency legally controls all activities. Section 193.2059 prescribes models for calculating a vapor dispersion exclusion zone (i.e., DEGADIS 2.1 and FEM3A). PHMSA's Administrator may also allow the use of alternate models that take into the account the same physical factors as the prescribed models and have been validated by experimental test data. It is noteworthy that the recognized lower flammable limit for methane is 5 percent, but § 193.2059(b) requires the use of 2.5 percent methane gas concentration for computing dispersion distances.

The impact of Phast 8.4 is that exclusion zone sizes may change, depending on the modeling calculations. However, increased risk can occur if the new model systematically underpredicts the vapor dispersion results. It is crucial that models permitted under §193.2059 are scientifically based and that their predictions agree well with large-scale experimental studies of LNG releases. Appendix A describes PHMSA's model review process and discusses the validation results of Phast 8.4.

PHMSA approved Phast 6.7 as an alternate model in 2011. Since then, there have been many new versions of Phast released and significant improvements have been made to the models and none of these are unavailable to v6.7 users. As discussed previously, the older versions of the model rely on increasingly obsolete software development technologies and platforms for which support is becoming difficult.

The changes to the models are by their nature technical and complex, but (see Section B for a detailed discussion) fall under the following broad categories:

1. Pools and Pool-cloud linking
2. AWD
3. INEX

The dimensions of flammable exclusion zones under the new model depend on the nature of the release, atmospheric conditions, substrate, plant design and mitigation measures, and many other factors. However, it is possible to draw some general conclusions about the performance of this version of the model given the experiment data collected and presented in this petition.[4] The Distance Safety Factor is a metric that compares model predicted maximum flammable distances with those measured in the experiment. Phast 6.7 had a median value of 0.96 across all experiments, whereas Phast 8.4 has a median of 1.09. This indicates that Phast 8.4 slightly overpredicted flammable distances in comparison to Phast 6.7.

While greater technical accuracy, including use of updated data and consideration of additional factors, is the primary benefit of Phast 8.4, the comparative data presented in the Petition, especially Table 15 in Appendix A, demonstrates that in all but one of the 17 trials, the cloud size was modeled as larger, correlating to a larger exclusion zone in most cases and more protection from the flammable vapor cloud.[5] The greater accuracy and slightly larger exclusion zone modeling demonstrate that in comparison to Phast 6.7, Phast 8.4 maintains and arguably increases the level of safety for the public from the threat of a flammable vapor cloud from an LNG facility. Thus, as required in 49 CFR § 193.2059, Phast 8.4 has been validated by experimental test data in test scenarios that take into the account the same physical factors as the prescribed models.

- Climate Change & Air Quality:

  While methane is a potent greenhouse gas, the model used for calculating exclusion zones will have no effect on the amount released during any potential incident. It is possible that Phast 8.4's calculation of a larger potential vapor dispersion cloud could require either control over a larger exclusion zone or additional plant design features to restrict the movement of a vapor cloud that could form following loss of containment.

  With broadly similar results, it is unlikely adoption of the new model will be a significant factor in incentivizing or disincentivizing the construction of an LNG facility or undertaking LNG production or development.

- Noise

  Noise levels are not relevant to the approval of Phast 8.4.

- Environmental Justice

  Phast 8.4 calculates the vapor dispersion distances based on the input materials, release conditions, and ambient weather conditions. The geographic location of the release does not impact the results; therefore, site-specific environmental justice analysis is not considered relevant. The application of a Phast model is not related to the population demographics surrounding a proposed LNG site. For a proposed facility, the lead agency would conduct an environmental justice analysis as part of the NEPA process that considers holistic facility siting.

[4] PHAST's Petition for Approval is available on this docket (PHMSA-2021-0041) at regulations.gov.

[5] For further explanation of the experiment that was an outlier and underpredicted gas dispersion distances, Burro 8 short, please see the explanations in Appendix A above Table 15 on page 38 of this document.

- Other

  This petition does not relate to a particular site, but rather to the method by which exclusion zones are calculated. Therefore, there will be no impact on the following environmental resources:

  - Aesthetics
  - Agricultural Resources
  - Biological Resources
  - Cultural Resources
  - Geology, Soils, and Mineral Resources
  - Land Use
  - Recreation
  - Transportation
  - Water Resources

F. Finding of No Significant Impact

PHMSA finds that the approval of the updated Phast 8.4 model will not result in a significant impact to the human environment, including human safety, and that the model complies with 49 CFR § 193.2059. This finding is based on the analysis in this FEA, including attachments to the FEA and accompanying documents located in https://www.regulations.gov/docket/PHMSA-2021-0041. PHMSA posted a draft environmental assessment, including a proposed finding of no significant impact, along with the accompanying documents and solicited comments from members of the public or interested parties. No comments appear in the docket after the close of comment period.

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H. Bibliography

An informal set of resources used within this document are presented below.

- Proposed LNG facilities listed in this document: https://www.ferc.gov/natural-gas/lng
- 49 CFR 193, and regulation § 193.2059 (a): https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-D/part-193
- Final decision letter from PHMSA for approval of Phast 6.7, with restrictions on usage: https://www.regulations.gov/document/PHMSA-2011-0075-0025
- Current petition to PHMSA for approval of Phast 8.4: https://www.regulations.gov/docket/PHMSA-2021-0041
- SUNDIALS numerical package used in Phast 8.4: https://computing.llnl.gov/projects/sundials

I. Abbreviations

AWD	Along wind diffusion: a new feature introduced into Phast 8.4 that considers the spreading of a vapor cloud in the direction of the wind in addition to the crosswind direction
DAE	Differential algebraic equations
FERC	Federal Energy Regulatory Commission
LNG	Liquefied natural gas
PHMSA	Pipeline and Hazardous Materials Safety Administration
NEPA	National Environmental Policy Act
ODEPACK	Suite of differential equation solvers from Lawrence Livermore National Laboratory. The numerical package used by Phast 6.7
SUNDIALS	Suite of differential equation solvers from Lawrence Livermore National Laboratory. The numerical package used by Phast 8.4
UDM	Unified Dispersion Model. The gas dispersion model incorporated into Phast.

APPENDIX A

PHMSA's Evaluation Process and Validation Results

On August 31, 2010, PHMSA issued advisory bulletin ADB-10-07 to provide guidance for obtaining approval on the use of the Model Evaluation Protocol (MEP 2010)[6] for alternative vapor dispersion models under Subpart B of 49 CFR Part 193. PHMSA evaluated the suitability of Phast versions 6.6 and 6.7 using the three-stage process described in the MEP 2010. In September 2016, an up-to-date version of the MEP (MEP 2016) was issued to include the following changes:

1. The inclusion of a prescribed approach for determining predicted maximum arc-wise gas concentrations. For each given arc, the maximum arc-wise concentration must be calculated as the maximum of the point-wise concentrations on that arc (i.e., the maximum of the predicted concentrations at the positions of the sensors that recorded concentrations in that experiment).

2. Wind-tunnel experiments will be modeled at wind-tunnel scale rather than at their equivalent full scale to avoid uncertainties associated with scaling experimental data.

3. Additional physical comparison parameters include the predicted distances to the measured maximum arc-wise concentrations, distances to the lower flammability limit (LFL) concentrations, and the predicted concentration at the measured distance to the LFL.

4. Additional Statistical Performance Measures (SPM) include the Concentration Safety Factor (CSF), Concentration Safety Factor to the Lower Flammability Limit (CSF_{LFL}), Distance Safety Factor (DSF), and Distance Safety Factor to the Lower Flammability Limit (DSF_{LFL}).

5. The model validation outputs must be provided in the model evaluation report.

6. Details of the uncertainty analyses must be undertaken to assess model sensitivity based on the requirements described in advisory bulletin ADB-10-07.

1. Expedited Review Process for Previously Approved Models

PHMSA considers the changes to previously reviewed models as either minor or major. The assessment of minor changes could be expedited to not unduly impede the use of new code developments that may include minor bug fixes and more extensive model improvements. PHMSA defines the changes as follows:

[6] The MEP includes the Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities Research Project: Technical Report (M.J. Ivings el als., April 2007) and supplemented in the Validation Database for Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities: Guide to the LNG Model Validation Database, Version 11.0 (S. Coldrick et al., May 2010).

1. Minor changes shall have no effect on model predictions, numeric, or model physics for LNG dispersion. Minor changes are meant to address four issues:
    a. Correction of software bugs or flaws within the software that make it perform less than optimally.
    b. Modification of the Graphic User Interface (GUI) of a program.
    c. Addition of new compatible hardware support.
    d. Modification of sub-models that are not relevant to LNG dispersion.
2. Major changes address the above four issues and also make advances to the scientific model for new and improved modeling capabilities for LNG dispersion. Major changes result in significant differences in the predicted point-wise concentrations as follows:
    a. For absolute predicted concentrations > 10 percent v/v, a relative difference of 1 percent in any of the predicted point-wise concentrations between the new and currently approved version of the model.
    b. For absolute predicted concentrations ≤ 10 percent v/v, an absolute difference of 0.1 percent v/v gas concentration in any of the predicted point-wise concentrations between the new and currently approved version of the model.

PHMSA conducts review of updated versions to previously approved models as follows:

1. For a model with minor changes, the petitioner must provide modeling results for the following subset of six LNG dispersion validation cases to confirm that the changes do not affect the results:

a. Burro 8
b. Coyote 5
c. Falcon 1
d. Thorney Island 47
e. Chemical Hazards Research Center (CHRC) Case B
f. BA Hamburg DAT223

2. For a model with major changes, the petitioner must provide a change-log report and provide modeling results for all cases in the model validation database. The change-log report must describe the changes that have been made to the new version of the model in the time since the previous version was approved by PHMSA. The report must comprise three parts (i.e., scientific assessment, verification, and validation) that describe the changes to these aspects of the model since the last PHMSA review.

2. Analysis

The changes between Phast version 6.7 and version 8.4 are considered major changes. DNV followed the guidance described in the MEP 2016 and the expedited process for a model with major changes in preparation of this Petition. DNV provided multiple versions of the summary reports, sensitivity simulation results and sensitivity reports, change-log reports, and an LNG model validation database. PHSMA has reviewed that information and determined that Phast version 8.4 may be used with an uncertainty factor of two to calculate the vapor dispersion exclusion zone for an LNG facility.

Scientific Assessment

The UDM is a one-dimensional integral dispersion model that models different stages in the evolution of a cloud: momentum jet, heavy gas, and passive. The core dispersion model comprises a set of differential-algebraic equations solved simultaneously for quantities including cloud mass, horizontal and vertical momentum, horizontal and vertical position, cloud width, mass centroid height, and others. The UDM can model continuous and instantaneous releases.

Major changes between version 6.7 and version 8.4 include model for pool-cloud linking, along-wind diffusion, updated numerical solver, pool model improvements, and INEX.

1. Model for pool-cloud linking – Phast version 6.7 used the concept of time-averaged segments. A dynamic pool was modeled by a set of these segments, each with a representative radius, evaporation rate, temperature etc. A calculation was made of the air entrainment over the pool for each segment. In Phast version 8.4, segments are replaced with observers. An observer can be imagined as a particle-sized sensor that is released at the center line of the cloud at a particular time and is then carried along with it. In the case of an evaporating pool, the observer starts from the upwind edge of the pool. The standard set of differential-algebraic equations are solved, with some additions and modifications to account for the presence of the pool.

2. AWD – For short-duration and time varying releases, the application of a steady-state model such as the UDM is likely to overpredict concentrations, especially in the far-field. In Phast version 8.4 a post-processed correction is based on Gaussian integration of observer concentrations with respect to downwind distance, using an empirically determined along-wind dispersion coefficient. For near-field concentrations or long duration releases AWD will not have a significant effect.

3. Updated numerical solver – The solver used in Phast version 6.7 was ODEPACK, developed by Alan Hindmarsh at Lawrence Livermore. This solver has been replaced by the SUNDIALS suite of solvers developed by the same group.

4. Pool model improvements – The UDM is linked to an updated version of the pool spreading and vaporization model, including the switch to the MacKay and Matsugu correlation for evaporation on land.

5. INEX – The UDM contains sub-model INEX for pressurized instantaneous or catastrophic rupture release scenarios. For 2-phase releases, the Phast version 6.7 model may underpredict rainout and over-predict rainout distance. An entirely new version is included with a better physical basis for 2-phase releases.

Verification

Verification was performed for the newly implemented models, as reported by DNV, and include the following models: gravity spreading correction (GSC), along-wind diffusion (AWD), pool-cloud linking, and INEX. The along-wind GSC post-processor model has been verified using analytical spreadsheet calculations of uncorrected dispersion results of unpressurized steady-state and finite-duration releases from a ground-level area source. The UDM AWD model has been verified analytically for passive dispersion of steady-state and finite-duration horizontal releases. The AWD and cloud-linking models have been verified for steady-state and time-varying releases by comparison to HEGADAS-S and HEGADAS-T,[7] respectively, for dispersion from a pool indicating good agreement to centerline concentrations in the far field. The UDM INEX model has been compared to an analytical model for cloud speed indicating good agreement.

In addition, the following verification cases were previously performed for Phast version 6.7 by DNV and are applicable to Phast version 8.4 since the core models have not changed since version 6.7. Pertaining to heavy gas dispersion, UDM numerical results of a two-dimensional isothermal ground level plume was compared to an analytical solution and was found to have identical agreement. The UDM was also verified against the HGSYSTEM model, HEGADAS, for heavy gas dispersion. For jet and near-field passive dispersion, the UDM numerical results were shown to be identical to an analytical solution for an elevated horizontal continuous jet of air. For far-field passive dispersion, the UDM numerical results were shown to be in close agreement with the vertical and crosswind dispersion coefficients and concentrations from the commonly adopted Gaussian passive dispersion formula.

Validation

The validation cases included for UDM comparison encompass only unobstructed experimental trials since the UDM does not have models applicable to obstructions and/or unlevel terrain.

[7] HEGADAS is a heavy gas dispersion program developed by Shell. HEGADAS-S is for steady state, and HEGADAS-T is for transient.

Therefore, the current validation study is limited to the following trials specified in the MEP 2016:

- LNG Field Trials: Maplin Sands 27, 34, 35; Burro 3, 7, 8, 9; Coyote 3, 5, 6.
- Other Field Trials: Thorney Island 45, 47.
- Wind Tunnel Experiments: CHRC A; BA-Hamburg DA0120 (Unobstructed), DAT223 (Unobstructed 2); and BA-TNO TUV0l, FLS.

Comparisons of the UDM to MEP 2016 quantitative acceptance criteria are shown in Table 1, which groups the comparisons according to all trials, field trials, and wind tunnel trials. Thus, the results are the statistical performance measures (SPM) averaged among the trials. The data is further grouped according to long and short time-averaging using two different data processing methods as indicated in the color-coded entries in the first column. Quantitative entries that are colored indicate the acceptance criteria was not met.

The UDM prediction of maximum arc-wise and point-wise concentration met all acceptance criteria with the exception of the factor of two criteria for grouped long time-averaged trials. In considering only the field trials, the UDM meets all acceptance criteria for long time-averaged comparisons. This contrasts to the *short* time-averaged field and scaled wind-tunnel trials, which do not meet all criteria. The performance of the short time-averaged field trials can be attributed to the Maplin Sands field trial comparisons. If these trials are excluded, then the UDM meets all criteria for the short time-averaged field trials as shown in Table 2.

All criteria for field trials were met for distance to measured maximum arc-wise gas concentration, but not for the wind tunnel trials. Regarding cloud width, the UDM met all acceptance criteria for all the trials. Pertaining to maximum arc-wise and point-wise concentrations, the UDM tends to be slightly over predictive for long time-averaged field trials and under predictive for short time-averaged field trials and wind tunnel trials. The UDM is under-predictive for wind tunnel trials by a factor of two to three for all comparisons except for cloud width which met all criteria.

Table 1: SPM Evaluation against Quantitative Assessment Criteria									
Data Set	Quantitative Criteria[8]								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Maximum Arc-wise Gas Concentration									
Unobstructed Trials* (long time avg.)	0.29	0.67	1.38	2.28	**0.39**	1.06	N/A	N/A	N/A
Unobstructed Trials** (long time avg.)	0.33	0.70	1.45	2.44	**0.40**	1.02	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	**0.49**	1.06	**2.24**	**15.37**	0.50	0.85	1.25	N/A	N/A
Unobstructed Field Trials (short time avg.)	**0.50**	1.06	**2.26**	**15.39**	0.50	0.85	1.23	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.06	0.52	0.94	1.86	0.55	1.43	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.00	0.56	1.01	2.07	0.56	1.36	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	**0.96**	0.98	**2.91**	**3.37**	**0.09**	**0.36**	N/A	N/A	N/A
Obstructed Trials (long time avg.)	**0.70**	0.53	N/A	N/A	**0.33**	**0.49**	N/A	N/A	N/A
Distance to Measured Maximum Arc-wise Gas Concentration									
Unobstructed Trials (long time avg.)	0.14	0.25	1.15	1.32	0.73	N/A	N/A	0.99	N/A
Unobstructed Trials (long time avg.)	0.13	0.25	1.15	1.31	0.61	N/A	N/A	0.99	N/A
Unobstructed Field Trials (short time avg.)	-0.01	0.13	0.99	1.15	0.93	N/A	N/A	1.08	1.02
Unobstructed Field Trials (short time avg.)	-0.01	0.13	0.99	1.14	0.85	N/A	N/A	1.07	1.02
Unobstructed Field Trials (long time avg.)	-0.09	0.16	0.91	1.19	0.86	N/A	N/A	1.19	N/A
Unobstructed Field Trials (long time avg.)	-0.10	0.15	0.90	1.18	0.80	N/A	N/A	1.20	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	**0.67**	0.46	**2.02**	1.66	**0.40**	N/A	N/A	0.50	N/A

[8] Table 5.3 in the MEP 2016 shows the full set of SPMs including the mean relative bias (MRB), mean relative square error (MRSE), fraction of predictions within a factor of two of the measurements (FAC2), geometric mean bias (MG), geometric variance (VG), CSF, CSF_{LFL}, DSF, and DSF_{LFL}.

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests with the exception of the Coyote tests where data after cloud ignition was excluded.
Colored entry indicates criteria was not met.

Table 1 (cont'd): SPM Evaluation against Quantitative Assessment Criteria

Data Set	Quantitative Criteria								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Maximum Point-wise Gas Concentration									
Unobstructed Trials* (long time avg.)	0.36	0.77	1.45	2.84	**0.40**	1.24	N/A	N/A	N/A
Unobstructed Trials** (long time avg.)	0.38	0.74	1.49	2.72	**0.43**	1.16	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	0.39	1.10	**2.03**	**50.87**	**0.43**	1.25	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	**0.42**	1.07	**2.09**	**46.14**	**0.44**	1.14	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.09	0.90	0.86	**3.82**	**0.41**	**2.13**	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.02	0.83	0.94	**3.42**	**0.48**	1.91	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	**0.63**	0.69	**1.98**	2.36	**0.39**	0.68	N/A	N/A	N/A
Cloud Width									
Unobstructed Trials (long time avg.)	0.01	0.14	0.98	1.21	0.95	N/A	N/A	N/A	N/A
Unobstructed Trials (long time avg.)	0.04	0.13	0.95	1.19	0.95	N/A	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.17	0.31	0.81	1.53	0.88	N/A	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.24	0.28	0.75	1.50	0.88	N/A	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	-0.11	0.01	1.12	1.01	1.00	N/A	N/A	N/A	N/A

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests with the exception of the Coyote tests where data after cloud ignition was excluded.

Colored entry indicates criteria was not met.

Table 2: SPM Evaluation against Quantitative Assessment Criteria without Maplin Sands trials									
Data Set	Quantitative Criteria								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Maximum Arc-wise Gas Concentration									
Unobstructed Trials* (long time avg.)	0.29	0.67	1.38	2.28	**0.39**	1.06	N/A	N/A	N/A
Unobstructed Trials** (long time avg.)	0.33	0.70	1.45	2.44	**0.40**	1.02	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	0.07	0.49	1.12	1.97	0.69	1.15	1.40	N/A	N/A
Unobstructed Field Trials (short time avg.)	0.08	0.49	1.13	1.98	0.69	1.14	1.40	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.06	0.52	0.94	1.86	0.55	1.43	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.00	0.56	1.01	2.07	0.56	1.36	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	**0.96**	0.98	**2.91**	**3.37**	**0.09**	**0.36**	N/A	N/A	N/A
Distance to Measured Maximum Arc-wise Gas Concentration									
Unobstructed Trials* (long time avg.)	0.14	0.25	1.15	1.32	0.73	N/A	N/A	0.99	N/A
Unobstructed Trials** (long time avg.)	0.13	0.25	1.15	1.31	0.61	N/A	N/A	0.99	N/A
Unobstructed Field Trials (short time avg.)	-0.04	0.12	0.97	1.14	0.92	N/A	N/A	1.10	1.09
Unobstructed Field Trials (short time avg.)	-0.03	0.12	0.97	1.14	0.85	N/A	N/A	1.09	1.09
Unobstructed Field Trials (long time avg.)	-0.09	0.16	0.91	1.19	0.86	N/A	N/A	1.19	N/A
Unobstructed Field Trials (long time avg.)	-0.10	0.15	0.90	1.18	0.80	N/A	N/A	1.20	N/A

Unobstructed Wind-Tunnel Trials (Scaled)	**0.67**	0.46	**2.02**	1.66	**0.40**	N/A	N/A	0.50	N/A

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests with the exception of the Coyote tests where data after cloud ignition was excluded.
Colored entry indicates criteria was not met.

Table 2 (cont'd): SPM Evaluation against Quantitative Assessment Criteria without Maplin Sands trials									
Data Set	**Quantitative Criteria**								
	-0.4 < MRB < 0.4	**MRSE < 2.3**	**0.67 < MG < 1.5**	**VG < 3.3**	**0.5 < FAC2**	**0.5 < CSF < 2**	**0.5 < CSF_LFL < 2**	**0.5 <DSF < 2**	**0.5 < DSF_LFL < 2**
Maximum Point-wise Gas Concentration									
Unobstructed Trials* (long time avg.)	0.36	0.77	1.45	2.84	**0.40**	1.24	N/A	N/A	N/A
Unobstructed Trials** (long time avg.)	0.38	0.74	1.49	2.72	**0.43**	1.16	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	-0.06	0.58	0.93	2.32	0.59	1.71	N/A	N/A	N/A
Unobstructed Field Trials (short time avg.)	-0.01	0.55	0.98	2.15	0.60	1.53	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.09	0.90	0.86	**3.82**	**0.41**	**2.13**	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	-0.02	0.83	0.94	**3.42**	**0.48**	1.91	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	**0.63**	0.69	**1.98**	2.36	**0.39**	0.68	N/A	N/A	N/A
Cloud Width									
Unobstructed Trials (long time avg.)	0.01	0.14	0.98	1.21	0.95	N/A	N/A	N/A	N/A
Unobstructed Trials (long time avg.)	0.04	0.13	0.95	1.19	0.95	N/A	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.17	0.31	0.81	1.53	0.88	N/A	N/A	N/A	N/A
Unobstructed Field Trials (long time avg.)	0.24	0.28	0.75	1.50	0.88	N/A	N/A	N/A	N/A
Unobstructed Wind-Tunnel Trials (Scaled)	-0.11	0.01	1.12	1.01	1.00	N/A	N/A	N/A	N/A

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows.
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests with the exception of the Coyote tests where data after cloud ignition was excluded.
Colored entry indicates criteria was not met.

With the exception of the wind tunnel trials, a large majority of UDM predictions of distance to measured maximum arc-wise gas concentration are within a factor of two as indicated by the FAC2 SPM. For all trials, most predictions of cloud width are within a factor of two. Note, ‘cloud width’ is a quantity calculated in the MEP 2016 for both experimental and simulated data and does not reflect the actual width of the cloud as indicated in experimental reports. For all trials, most predictions of the maximum arc-wise concentration for long time-averaged field trials are within a factor of two. For short time-averaged grouped field trials, the UDM prediction of distance to the LFL indicates good agreement.

The above discussion pertains to statistical measures that have been averaged among all trials or trials within a group and thus it does not reveal performance for individual trials. To gain further insight into UDM performance, it is useful to examine predictions for individual trials as provided in Figure 1 and Tables 3 through 6. Note, the MEP 2016 does not plot the Netherlands Organisation for Applied Scientific Research (BA-TNO) TUV01 trial in Figure 1 because the sensors are not positioned on arcs. However, the experimental and model data for the TUV01 trial was used to generate statistical performance measures for point-wise comparison.

The comparison of UDM predictions to measured maximum arc-wise gas concentrations for the Maplin Sands trials indicates significant underprediction and are not within a factor of two as shown in Figure 1. Burro 8 and the wind tunnel trials are also underpredicted and are not within a factor of two, whereas some of the Coyote trial predictions are overpredicted and are not within a factor of two as indicated in Figure 1 and Table 3.

The concentration safety factor and the predicted concentration at the measured distance to the LFL shown in Table 3 indicate that the UDM tends to overpredict these two metrics for most field trials except for the Maplin Sands trials, the Thorny Island 45 trial, the Burro 8 trial, and all wind tunnel trials. The maximum *point-wise* concentration comparison shown in Table 4 indicates similar trends to the *arc-wise* concentration comparison. The UDM tends to have better agreement to maximum point-wise concentration in the far field rather than the near field locations.

With regard to prediction of distance to maximum arc-wise concentration, the UDM tends to be over-predictive for most field trials, except for the Maplin Sands, Burro 8, and the wind tunnel trials, as shown in Table 5. The predicted distance at which the measured maximum arc-wise concentration occurs and the distance to LFL shown in Table 5 also indicates a similar trend. The UDM tends to overpredict MEP 2016 calculated cloud width as shown in Table 6 for the individual trials.

Overall, the short versus long time-averaged results indicate slightly better performance for the Burro and Coyote trials as shown in Table 7 and Tables 8. Rolling averages and fixed-window averages are comparable in performance for either short or long time-averaged results. Longer time averages result in lower maximum arc-wise and point-wise gas concentrations. Similarly, longer time averages of experimental data results in lower concentrations as peak concentrations are smoothed out over longer time averages. For higher wind speeds and lower atmospheric stability, where turbulent fluctuations and cloud meander may have higher amplitudes, there is a greater reduction in gas concentration when averaged. Short time-averages are more appropriate for flammable hazards and should be used when predicting flammable vapor centerline concentrations.

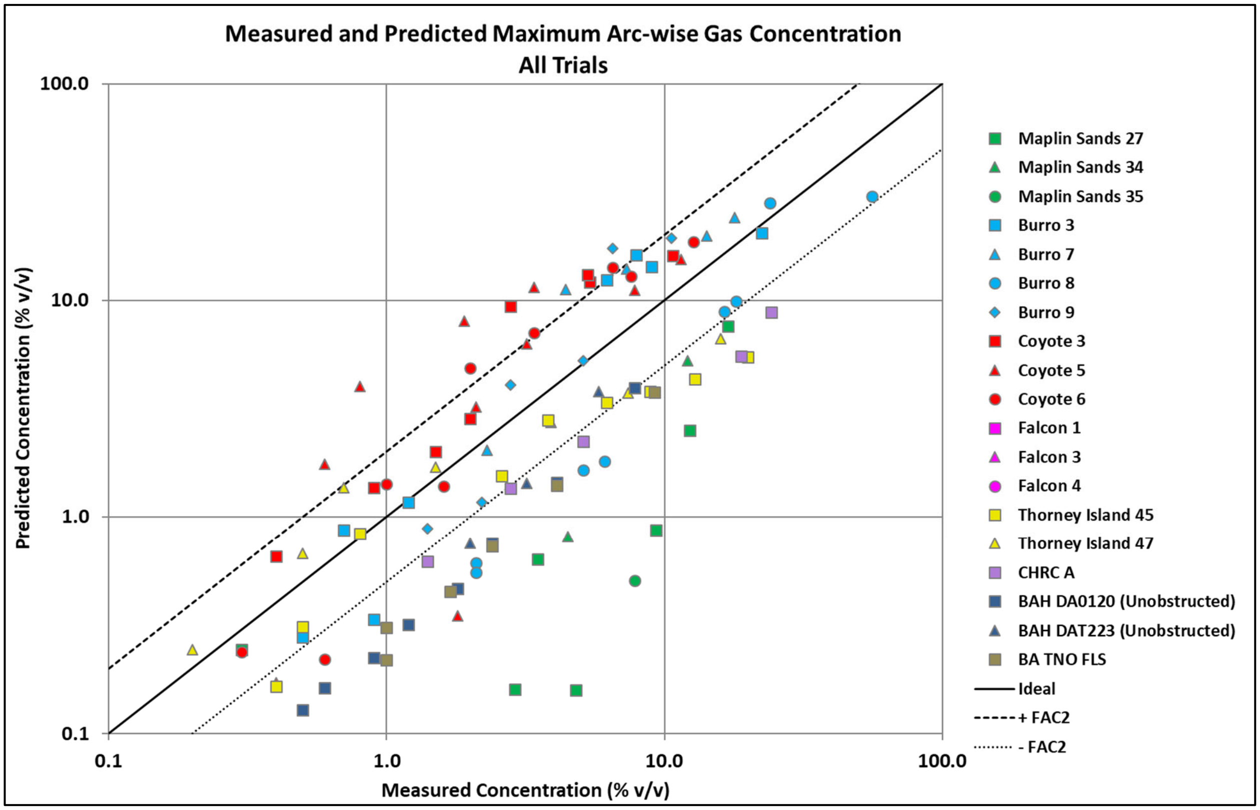

Figure 1: Predicted versus measured maximum arc-wise gas concentration for all trials.

Table 3: SPM Evaluation of Maximum Arc-wise Gas Concentration Individual Trials									
Data Set	**Quantitative Criteria**								
	-0.4 < MRB < 0.4	**MRSE < 2.3**	**0.67 < MG < 1.5**	**VG < 3.3**	**0.5 < FAC2**	**0.5 < CSF < 2**	**0.5 < CSF_LFL < 2**	**0.5 <DSF < 2**	**0.5 < DSF_LFL < 2**
Maximum Arc-wise Gas Concentration									
Maplin Sands 27 (short*)	**1.36**	2.18	**8.25**	**352.79**	**0.13**	**0.23**	*N/M****	N/A	N/A
Maplin Sands 34 (short)	**1.09**	1.28	**3.58**	**6.20**	**0.00**	**0.31**	**0.20**	N/A	N/A
Maplin Sands 35 (short)	**1.86**	**3.48**	**41.13**	**>1000**	**0.00**	**0.04**	*N/M*	N/A	N/A
Burro 3 (short)	0.14	0.26	1.17	1.35	0.75	0.96	1.38	N/A	N/A
Burro 3 (long**)	-0.25	0.32	0.77	1.41	0.50	1.46	N/A	N/A	N/A
Burro 7 (short)	-0.19	0.20	0.82	1.23	1.00	1.32	1.04	N/A	N/A
Burro 7 (long)	-0.36	0.29	0.68	1.39	0.67	1.61	N/A	N/A	N/A
Burro 8 (short)	**0.84**	0.77	**2.50**	2.55	0.50	**0.42**	**0.29**	N/A	N/A
Burro 8 (long)	**0.66**	0.70	**2.07**	2.37	0.50	0.58	N/A	N/A	N/A
Burro 9 (short)	0.00	0.24	1.00	1.29	1.00	1.13	1.01	N/A	N/A
Burro 9 (long)	-0.28	0.39	0.74	1.55	0.67	1.58	N/A	N/A	N/A
Coyote 3 (short)	-0.02	0.76	1.14	**4.25**	0.60	1.32	**2.17**	N/A	N/A
Coyote 3 (long)	**-0.71**	0.57	**0.47**	1.97	0.50	**2.25**	N/A	N/A	N/A
Coyote 5 (short)	-0.07	0.53	0.98	2.04	0.80	1.29	1.67	N/A	N/A
Coyote 5 (long)	**-0.77**	1.22	**0.41**	**4.98**	**0.00**	**3.19**	N/A	N/A	N/A
Coyote 6 (short)	-0.18	0.45	0.83	1.67	**0.40**	1.46	**2.24**	N/A	N/A
Coyote 6 (long)	-0.33	0.23	0.71	1.28	0.75	1.50	N/A	N/A	N/A
Thorney Island 45 (long)	**0.62**	0.50	**1.95**	1.81	0.56	0.55	N/A	N/A	N/A
Thorney Island 47 (long)	0.04	0.28	1.05	1.35	0.83	1.09	N/A	N/A	N/A
CHRC A (S†)	**0.86**	0.75	**2.51**	2.42	**0.00**	**0.40**	N/A	N/A	N/A
BA Hamburg DA01020 (S)	**1.06**	1.15	**3.29**	**4.32**	**0.13**	**0.31**	N/A	N/A	N/A
BA Hamburg DAT223 (S)	**0.70**	0.53	**2.09**	1.81	**0.33**	**0.49**	N/A	N/A	N/A
BA TNO FLS (S)	**1.07**	1.16	**3.32**	**4.38**	**0.00**	**0.31**	N/A	N/A	N/A

*short time-averaged

**long time-averaged

***predicted arc-wise maximum concentrations do not monotonically decay

†equivalent field scale

Colored entry indicates criteria was not met.

Table 4: SPM Evaluation of Maximum Point-wise Gas Concentration Individual Trials									
Data Set	**Quantitative Criteria**								
	-0.4 < MRB < 0.4	**MRSE < 2.3**	**0.67 < MG < 1.5**	**VG < 3.3**	**0.5 < FAC2**	**0.5 < CSF < 2**	**0.5 < CSF_LFL < 2**	**0.5 <DSF < 2**	**0.5 < DSF_LFL < 2**
Maximum Point-wise Gas Concentration									
Maplin Sands 27 (short*)	**1.39**	2.22	**12.31**	**>1000**	**0.08**	**0.22**	N/A	N/A	N/A
Maplin Sands 34 (short)	**1.03**	1.12	**3.23**	**4.44**	**0.00**	**0.33**	N/A	N/A	N/A
Maplin Sands 35 (short)	**1.83**	**3.36**	**33.30**	**>1000**	**0.00**	**0.05**	N/A	N/A	N/A
Burro 3 (short)	0.32	0.39	1.45	1.78	0.73	0.81	N/A	N/A	N/A
Burro 3 (long**)	**-0.50**	0.84	**0.55**	**3.48**	**0.27**	**2.79**	N/A	N/A	N/A
Burro 7 (short)	**-0.42**	0.95	**0.56**	**5.67**	0.50	**3.65**	N/A	N/A	N/A
Burro 7 (long)	**-0.62**	1.09	**0.45**	**7.17**	**0.20**	**4.47**	N/A	N/A	N/A
Burro 8 (short)	0.23	0.36	1.28	1.52	0.72	0.93	N/A	N/A	N/A
Burro 8 (long)	-0.02	0.32	0.98	1.45	0.61	1.22	N/A	N/A	N/A
Burro 9 (short)	-0.04	0.30	0.96	1.38	0.70	1.21	N/A	N/A	N/A
Burro 9 (long)	**-0.45**	0.74	**0.57**	2.89	0.60	**2.54**	N/A	N/A	N/A
Coyote 3 (short)	0.07	0.61	1.14	2.49	0.57	1.22	N/A	N/A	N/A
Coyote 3 (long)	-0.33	0.86	0.73	**3.49**	**0.33**	1.99	N/A	N/A	N/A
Coyote 5 (short)	-0.05	0.47	0.96	1.80	0.64	1.35	N/A	N/A	N/A
Coyote 5 (long)	**-0.76**	1.12	**0.39**	**5.37**	**0.25**	**3.56**	N/A	N/A	N/A
Coyote 6 (short)	**-0.55**	0.95	**0.51**	**3.96**	**0.29**	**2.93**	N/A	N/A	N/A
Coyote 6 (long)	**-0.91**	1.25	**0.31**	**8.93**	**0.40**	**4.70**	N/A	N/A	N/A
Thorney Island 45 (long)	**0.70**	0.91	**2.14**	3.22	**0.41**	0.61	N/A	N/A	N/A
Thorney Island 47 (long)	**0.48**	1.15	**1.73**	**6.29**	**0.47**	1.02	N/A	N/A	N/A
CHRC A (S†)	**0.52**	0.63	**1.72**	2.19	**0.43**	0.86	N/A	N/A	N/A
BA Hamburg DA01020 (S)	**1.06**	1.15	**3.29**	**4.32**	**0.13**	**0.31**	N/A	N/A	N/A
BA Hamburg DAT223 (S)	**0.61**	0.45	**1.90**	1.66	**0.38**	0.55	N/A	N/A	N/A
BA TNO TUV01 (S)	**0.48**	0.38	**1.67**	1.58	0.75	0.66	N/A	N/A	N/A
BA TNO FLS (S)	**0.77**	0.79	**2.34**	2.69	**0.32**	**0.50**	N/A	N/A	N/A

*short time-averaged

**long time-averaged

†equivalent field scale

Colored entry indicates criteria was not met.

Table 5: SPM Evaluation of Distance to Measured Maximum Arc-wise Gas Concentration Individual Trials									
Data Set	**Quantitative Criteria**								
	-0.4 < MRB < 0.4	**MRSE < 2.3**	**0.67 < MG < 1.5**	**VG < 3.3**	**0.5 < FAC2**	**0.5 < CSF < 2**	**0.5 < CSF_LFL < 2**	**0.5 <DSF < 2**	**0.5 < DSF_LFL < 2**
Distance to Measured Maximum Arc-wise Gas Concentration									
Maplin Sands 27 (short*)	*N/M****	*N/M*	*N/M*	*N/M*	*N/M*	*N/M*	*N/M*	*N/M*	*N/M*
Maplin Sands 34 (short)	**0.57**	0.32	**1.79**	1.41	N/A	N/A	N/A	0.56	0.54
Maplin Sands 35 (short)	*N/M*	*N/M*	*N/M*	*N/M*	N/A	*N/M*	*N/M*	*N/M*	*N/M*
Burro 3 (short)	0.12	0.11	1.13	1.12	*N/M*	N/A	N/A	0.93	1.14
Burro 3 (long**)	-0.26	0.30	0.76	1.41	*N/M*	N/A	N/A	1.52	N/A
Burro 7 (short)	-0.22	0.15	0.80	1.17	N/A	N/A	N/A	1.31	1.03
Burro 7 (long)	-0.33	0.19	0.71	1.23	N/A	N/A	N/A	1.46	N/A
Burro 8 (short)	**0.65**	0.43	**1.96**	1.61	N/A	N/A	N/A	0.51	**0.47**
Burro 8 (long)	**0.45**	0.33	**1.61**	1.44	N/A	N/A	N/A	0.67	N/A
Burro 9 (short)	-0.07	0.10	0.93	1.11	N/A	N/A	N/A	1.13	1.01
Burro 9 (long)	-0.21	0.18	0.80	1.21	N/A	N/A	N/A	1.34	N/A
Coyote 3 (short)	-0.23	0.07	0.79	1.07	*N/M*	N/A	N/A	1.27	1.24
Coyote 3 (long)	-0.15	0.07	0.86	1.07	*N/M*	N/A	N/A	1.19	N/A
Coyote 5 (short)	-0.15	0.05	0.86	1.06	N/A	N/A	N/A	1.18	1.35
Coyote 5 (long)	-0.36	0.23	0.69	1.29	N/A	N/A	N/A	1.54	N/A
Coyote 6 (short)	-0.15	0.06	0.86	1.06	N/A	N/A	N/A	1.18	1.36
Coyote 6 (long)	-0.13	0.03	0.88	1.03	N/A	N/A	N/A	1.15	N/A
Thorney Island 45 (long)	0.26	0.09	1.29	1.10	N/A	N/A	N/A	0.78	N/A
Thorney Island 47 (long)	-0.16	0.03	0.85	1.03	*N/M*	N/A	N/A	1.17	N/A
CHRC A (S†)	**0.50**	0.25	**1.67**	1.31	N/A	N/A	N/A	0.60	N/A
BA Hamburg DA01020 (S)	**0.72**	0.53	**2.14**	1.79	N/A	N/A	N/A	**0.47**	N/A
BA Hamburg DAT223 (S)	**0.59**	0.35	**1.84**	1.45	N/A	N/A	N/A	0.55	N/A
BA TNO FLS (S)	**0.76**	0.59	**2.24**	1.92	N/A	N/A	N/A	**0.45**	N/A

*short time-averaged

**long time-averaged

***predicted arc-wise maximum concentrations do not monotonically decay

†equivalent field scale

Colored entry indicates criteria was not met.

Table 6: SPM Evaluation Cloud Width Individual Trials									
Data Set	Quantitative Criteria								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Cloud Width									
Burro 3 (long)*	-0.19	0.04	1.21	1.04	1.00	N/A	N/A	N/A	N/A
Burro 9 (long)	**-0.43**	0.19	**1.55**	1.21	1.00	N/A	N/A	N/A	N/A
Coyote 3 (long)	0.05	0.00	0.95	1.00	1.00	N/A	N/A	N/A	N/A
Coyote 6 (long)	-0.28	0.08	1.32	1.08	1.00	N/A	N/A	N/A	N/A
CHRC A (S†)	-0.11	0.01	1.12	1.01	1.00	N/A	N/A	N/A	N/A
BA TNO FLS (S)	-0.11	0.01	1.11	1.01	1.00	N/A	N/A	N/A	N/A

*long time-averaged

†equivalent field scale

Colored entry indicates criteria was not met.

Table 7: Evaluation of Maximum Arc-wise Gas Concentration Burro and Coyote trials, fixed and rolling averages									
Data Set	Quantitative Criteria								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Maximum Arc-wise Gas Concentration									
Burro 3 (short)*	0.14	0.26	1.17	1.35	0.75	0.96	1.38	N/A	N/A
Burro 3 (short)**	0.20	0.29	1.24	1.38	0.75	0.92	1.38	N/A	N/A
Burro 3 (long)	-0.25	0.32	0.77	1.41	0.50	1.46	N/A	N/A	N/A
Burro 3 (long)	-0.18	0.34	0.83	1.44	0.75	1.38	N/A	N/A	N/A
Burro 7 (long)	-0.36	0.29	0.68	1.39	0.67	1.61	N/A	N/A	N/A
Burro 7 (long)	-0.34	0.28	0.70	1.36	0.67	1.57	N/A	N/A	N/A
Burro 8 (short)	**0.84**	0.77	**2.50**	2.55	0.50	**0.42**	**0.29**	N/A	N/A
Burro 8 (short)	**0.84**	0.77	**2.50**	2.55	0.50	**0.42**	**0.29**	N/A	N/A
Burro 8 (long)	**0.66**	0.70	**2.07**	2.37	0.50	0.58	N/A	N/A	N/A
Burro 8 (long)	**0.73**	0.71	**2.24**	2.44	0.50	0.50	N/A	N/A	N/A
Burro 9 (long)	-0.28	0.39	0.74	1.55	0.67	1.58	N/A	N/A	N/A
Burro 9 (long)	-0.25	0.37	0.76	1.51	0.67	1.54	N/A	N/A	N/A
Coyote 3 (short)	-0.02	0.76	1.14	**4.25**	0.60	1.32	**2.17**	N/A	N/A
Coyote 3 (short)	-0.02	0.76	1.14	**4.25**	0.60	1.32	**2.17**	N/A	N/A
Coyote 3 (long)	**-0.71**	0.57	**0.47**	1.97	0.50	**2.25**	N/A	N/A	N/A
Coyote 3 (long)	-0.22	0.99	0.90	**5.23**	**0.40**	1.76	N/A	N/A	N/A
Coyote 5 (short)	-0.07	0.53	0.98	2.04	0.80	1.29	1.67	N/A	N/A
Coyote 5 (short)	-0.07	0.52	0.99	2.03	0.80	1.28	1.67	N/A	N/A
Coyote 5 (long)	**-0.77**	1.22	**0.41**	**4.98**	**0.00**	**3.19**	N/A	N/A	N/A
Coyote 5 (long)	**-0.75**	1.18	**0.42**	**4.63**	**0.00**	**3.08**	N/A	N/A	N/A

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows.
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests with the exception of the Coyote tests where data after cloud ignition was excluded.
Colored entry indicates criteria was not met.

Table 8: Evaluation of Maximum Point-wise Gas Concentration Burro and Coyote trials									
Data Set	Quantitative Criteria								
	-0.4 < MRB < 0.4	MRSE < 2.3	0.67 < MG < 1.5	VG < 3.3	0.5 < FAC2	0.5 < CSF < 2	0.5 < CSF_LFL < 2	0.5 <DSF < 2	0.5 < DSF_LFL < 2
Maximum Point-wise Gas Concentration									
Burro 3 (short)*	0.32	0.39	1.45	1.78	0.73	0.81	N/A	N/A	N/A
Burro 3 (short)**	0.40	0.43	**1.57**	1.82	0.69	0.75	N/A	N/A	N/A
Burro 3 (long)	**-0.50**	0.84	**0.55**	**3.48**	**0.27**	**2.79**	N/A	N/A	N/A
Burro 3 (long)	-0.04	0.38	0.98	1.61	0.67	1.22	N/A	N/A	N/A
Burro 7 (short)	**-0.42**	0.95	**0.56**	**5.67**	0.50	**3.65**	N/A	N/A	N/A
Burro 7 (short)	-0.32	0.72	0.66	3.15	0.58	**2.59**	N/A	N/A	N/A
Burro 7 (long)	**-0.62**	1.09	**0.45**	**7.17**	**0.20**	**4.47**	N/A	N/A	N/A
Burro 7 (long)	**-0.58**	1.06	**0.46**	**7.06**	**0.20**	**4.45**	N/A	N/A	N/A
Burro 8 (short)	0.23	0.36	1.28	1.52	0.72	0.93	N/A	N/A	N/A
Burro 8 (short)	0.29	0.37	1.37	1.54	0.72	0.86	N/A	N/A	N/A
Burro 8 (long)	-0.02	0.32	0.98	1.45	0.61	1.22	N/A	N/A	N/A
Burro 8 (long)	0.05	0.37	1.05	1.53	0.68	1.17	N/A	N/A	N/A
Burro 9 (short)	-0.04	0.30	0.96	1.38	0.70	1.21	N/A	N/A	N/A
Burro 9 (short)	-0.04	0.30	0.96	1.38	0.70	1.21	N/A	N/A	N/A
Burro 9 (long)	**-0.45**	0.74	**0.57**	2.89	0.60	**2.54**	N/A	N/A	N/A
Burro 9 (long)	-0.29	0.53	0.71	2.00	0.70	1.91	N/A	N/A	N/A
Coyote 3 (short)	0.07	0.61	1.14	2.49	0.57	1.22	N/A	N/A	N/A
Coyote 3 (short)	0.07	0.61	1.14	2.49	0.57	1.22	N/A	N/A	N/A
Coyote 3 (long)	-0.33	0.86	0.73	**3.49**	**0.33**	1.99	N/A	N/A	N/A
Coyote 3 (long)	-0.31	0.83	0.75	**3.35**	0.50	1.93	N/A	N/A	N/A
Coyote 5 (short)	-0.05	0.47	0.96	1.80	0.64	1.35	N/A	N/A	N/A
Coyote 5 (short)	-0.05	0.47	0.96	1.80	0.64	1.35	N/A	N/A	N/A
Coyote 5 (long)	**-0.76**	1.12	**0.39**	**5.37**	**0.25**	**3.56**	N/A	N/A	N/A
Coyote 5 (long)	**-0.74**	1.11	**0.40**	**5.30**	**0.25**	**3.53**	N/A	N/A	N/A
Coyote 6 (short)	**-0.55**	0.95	**0.51**	**3.96**	**0.29**	**2.93**	N/A	N/A	N/A
Coyote 6 (short)	**-0.55**	0.95	**0.51**	**3.96**	**0.29**	**2.93**	N/A	N/A	N/A
Coyote 6 (long)	**-0.91**	1.25	**0.31**	**8.93**	**0.40**	**4.70**	N/A	N/A	N/A
Coyote 6 (long)	**-0.90**	1.23	**0.32**	**8.51**	**0.40**	**4.62**	N/A	N/A	N/A

* Grouped SPM values based on field-scale concentration measurements taken during fixed averaging windows.
** Grouped SPM values based on field-scale concentration measurements taken as rolling averages across duration of tests except for the Coyote tests where data after cloud ignition was excluded.
Colored entry indicates criteria was not met.

For siting purposes, the distance to the LFL and ½ LFL are of main interest when using a model to perform vapor-gas dispersion calculations. Further review of UDM predictions of distance to the LFL was conducted and is provided in Table 9, which shows distances calculated directly from the UDM and calculated within the MEP 2016. The MEP 2016 calculates distances to the LFL from maximum arc-wise concentrations and applies the same procedure for both prediction and measurement. Table 9 also provides the distance to the ½ LFL calculated directly from the UDM. The ratio of the distance to LFL from the UDM predictions to those calculated in the MEP 2016 is also provided in Table 9 and indicates that the UDM overpredicts the distance to the LFL for all cases with exception of the Maplin Sands trials and Burro 8 trial.

It should be noted that the Maplin Sands trials had large variations in wind speed and direction during the tests, which could significantly affect concentration measurements. Maplin Sands trial 35 had the most variation, while trial 27 had the least. Note, the SPM results for the UDM indicate the worst performance in trial 35 and the best in trial 27. Since tabulated experimental data for wind speed and direction over time is not provided in the MEP 2016, it is difficult for models to accurately represent the wind conditions, possibly limiting the UDM's performance.

Also of note, the Burro 8 trial was significantly affected by the surrounding terrain compared to other tests due to the extent of the cloud. The terrain created a significantly asymmetric cloud causing much higher concentrations in the left lobe. Without an accurate representation of the terrain, a model will not capture this asymmetry, resulting in a maximum arc-wise concentration that will be underpredicted. The point-wise concentration comparisons may perform much better because other measurement locations on an arc are included, which may offset the poorer performance for locations in the left lobe to provide acceptable SPM values. The performance of the UDM for Burro 8 met all performance measures for maximum point-wise concentrations for both short and long-time averaging, but not for maximum arc-wise concentrations.

If the Burro and Coyote trials are compared for the LFL distance, as calculated by the UDM directly, it is evident that the Burro 8 is an outlier because the distance is considerably underpredicted, particularly for short time-averaged results. The predicted distance to ½ LFL is also below the LFL distance based on experimental data. Even if the predicted LFL distances were doubled for either short or long time-averaged results, the distance would still be below that based on experimental data.

The significance of the Burro 8 trial is that low wind speeds (i.e., less than 2 meters per second (m/s)) and high atmospheric stabilities are particularly pertinent to the current federal regulations in 49 C.F.R. Part 193. Given the performance regarding the predicted distance to the LFL and ½ LFL, PHMSA recommends that at least a distance safety factor of two is used for short time averages, which is more appropriate for predicting flammable regions and consistent with PHMSA's current regulatory standard in § 193.2059(b) that requires use of 2.5 percent gas concentration or ½ LFL for methane.

Table 9: Comparison of distance to LFL				
Distance to LFL (m)				Ratio
Trial - stability, wind speed (m/s)	**$LFL_{p\text{-}Phast}$, (calculated by Phast) (LFL, ½LFL)**	**Calculated in MEP from Phast maximum arc-wise predictions**	**$LFL_{m\text{–}MEP}$, (calculated in MEP from maximum arc-wise measurements)**	**$LFL_{p\text{-}Phast}$/ $LFL_{m\text{-}MEP}$**
Maplin Sands 27 - C/D, 5.5	113, 169	N/M	177	0.63
Maplin Sands 34 – D, 8.6	136, 204	90	167	0.81
Maplin Sands 35 – D, 9.8	136, 205	N/M	184	0.73
Burro 3 Long – C, 5.58	287, 369	214	190	1.68
Burro 3 short – C, 5.58	283, 374			1.55
Burro 7 long – D, 8.75	302, 406	270	264	1.35
Burro 7 short – D, 8.75	304, 417			1.16
Burro 8 long – E, 1.94	191, 312	214	455	0.49
Burro 8 short – E, 1.94	191, 315			0.42
Burro 9 long – D, 5.94	409, 549	406	406**	1.08
Burro 9 short – D, 5.94	411, 553			1.01
Coyote 3 long – C, 6.77	330, 426	254	206	1.69
Coyote 3 short – C, 6.77	331, 429			1.61
Coyote 5 long – C, 10.47	339, 442	329	245	1.51
Coyote 5 short- C, 10.47	341, 449			1.40
Coyote 6 long – D, 5.04	367, 493	290	219	1.78
Coyote 6 short – D, 5.04	369, 499			1.60

*Predicted arc-wise maximum concentrations do not monotonically decay.
**Rapid phase transition explosions caused momentary artificial spikes at 400 m arc location which if removed reduces the LFL distance to 270 m as reported by Morgan, et al., "Dispersion Phenomenology of LNG Vapor in the Burro and Coyote LNG Experiments", Transactions of the ASME, 109, November 1987, pp. 952-960.
Colored entry indicates criteria was not met.

Sensitivity Analysis

A sensitivity analysis was conducted by DNV based on variations previously performed as part of its petition for use of Phast versions 6.6 and 6.7. DNV utilized a set of variations from the Federal Energy Regulatory Commission's July 2011 report entitled, *Evaluation of DEGADIS 2.1 Using Advisory Bulletin ADB-10-07*,[9] which provides a range of values for pertinent input parameters. Since this submission pertains to a code upgrade, only a subset of trials was required for evaluation rather than all MEP 2016 trials.

[9] *Available at* https://www.ferc.gov/sites/default/files/2020-04/EvaluationofDEGADIS2.1UsingAdvisoryBulletinADB-10-07Report.pdf

The cases evaluated were the following:

- Maplin Sands 27
- Burro 8
- Burro 9
- Coyote 3
- Thorney Island 45
- BA-Hamburg 223
- CHRCA

The parameters considered for variation for the above trials are provided in Table 10. The substrate 'shallow open water' model allows for ice formation whereas the 'deep open water' model excludes this.

Table 10: Parameter variations for field trials

Variation		Maplin Sands 27	Burro 8	Burro 9	Coyote 3	Thorney Island 45	BA-Hamburg 223	CHRCA
Wind speed	Base	5.5	1.94	5.94				
(m/s)	Low	4.4	1.67	5.20				
	High	6.1	2.21	6.68				
Wind direction	Base		234.8	232.0				
(degrees)	Low		229.3	227.6				
	High		240.3	236.4				
Stability class	Base	C/D	D	D		F		
	Low	C	C/D	C/D		E		
	High	D	E	E				
Surface	Base	0.3	0.2	0.2	0.2	10	3.93	108
roughness (mm)	Low	0.1				0.2	1	10.8
	High	1	10	10	10	30	10	
Pressure (Pa)	Base		94830	94830	93620			
	Alt		101325	101325	101325			
Humidity (%)	Base	53		14.4	11.3			
	Alt	63		6.5	3.5			
Substrate	Base	Deep	Shallow	Shallow	Shallow			
	Alt	Shallow	Deep	Deep	Deep			
Molecular weight (kg/kmol)	Base	16.04	16.04	16.04	16.04			
	Alt	17.11	18.83	18.83	19.52			

Table 11 provides a comparison of the effect of the parameter variation, assessed by multivariate regression. The regression analysis provides standardized coefficients for a regression equation involving all parameters of concentration versus parameters. The formula is:

$$Concentration = \sum_{i=1}^{n} coefficient_i * parameter_i + constant$$

The coefficients in Table 11 are standardized and represent the mean change in the concentration given a one standard deviation change in the input parameter. The standardization allows the input parameters to be put on the same scale, thereby allowing them to be ranked and compared directly. A positive sign of the standardized regression coefficient indicates a direct relationship between the concentration and the input parameter, and conversely a negative sign indicates an inverse relationship.

Table 11: Parameter standardized regression coefficients

	Surface roughness	Wind speed	Wind direction	Stability	Humidity	Substrate	Mol. weight	Atm. pressure
Maplin Sands 27	-0.066	-0.067		0.083	-0.049	-0.034	0.039	
Burro 8 (short)	-1.26	0.05	-0.22	-0.63		-0.11	-0.36	-0.21
Burro 8 (long)	-1.02	0.00	-0.03	-0.4		-0.24	-0.33	-0.29
Burro 9 (short)	-0.67	-0.1	-0.01	-0.53	-0.05	0.19	-0.1	0.00
Burro 9 (long)	-0.62	-0.03	-0.02	-0.26	-0.1	0.1	-0.1	0.05
TI 45	-0.249			0.353	0.09			
Coyote 3	-1.06					0.19	-0.3	-0.15
DAT223	-0.328							
CHRCA	-1.63							

The results indicate that surface roughness is the most impactful parameter for all the cases, except for the Maplin Sands 27 trial where wind speed was slightly more impactful. The negative sign indicates that an increase in surface roughness causes a decrease in concentration for all cases.

The surface roughness experimental values have the largest uncertainties and mostly provide the upper and lower bound of the predictions compared to the other parameters. The surface roughness values specified in the MEP 2016 are generally low and result in higher concentrations and longer dispersion distances to the LFL, which may cause the model to appear more conservative than it is. Less conservative parameters cause the model to underpredict concentrations by a greater margin, but still within the quantitative acceptance criteria. Phast version 8.4 must be used in accordance with 49 C.F.R. § 193.2059, which specifies the surface roughness of 0.03 meters or higher. The 0.03-meter surface roughness prescribed in 49 C.F.R. § 193.2059 generally provides reasonable, or conservative, results for LNG releases that disperse over land. Higher surface roughness values may be used if it can be shown that the terrain both upwind and downwind of the vapor cloud has dense vegetation and that the vapor cloud height is more than 10 times the height of the obstacles encountered by the vapor cloud. Lower surface roughness values may be considered for LNG releases that disperse over water. Site location should be included with the siting package for use in exclusion zone calculations.

In addition to surface roughness, the sensitivity analysis also includes parameters pertinent to atmospheric conditions, namely, wind speed and direction, stability, humidity, and pressure. Table 11 indicates that an increase in wind speed results in a decrease in concentration for the Maplin Sands 27 trial. Burro 9 trial also has an inverse relationship with wind speed. However, Burro 8 trial has a direct relationship for short time-averaging and a negligible effect for long time-averaging. An increase in wind direction results in a decrease in concentration for both the Burro 8 and 9 trials.

An increase in stability results in an increase in concentration for the Maplin Sands 27 and Thorney Island 45 trials, but not for the Burro 8 and 9 trials. Interestingly, for the short time-averaged Burro 8 trial, a lower atmospheric stability resulted in the best performance with regards to the statistical measures for maximum arc-wise concentration and DSL_{LFL}. The DSL_{LFL} increased by 48 percent with a value of 0.69 versus 0.47. Experiments have shown that lower atmospheric stabilities generally produce lower downwind concentrations and dispersion distances, and higher atmospheric stabilities produce higher downwind concentrations and dispersion distances. The Burro trial results do not follow this trend.

An increase in humidity results in a decrease in concentration for all cases except for Thorney Island 45 trial. Experimental ambient temperature and surface temperature had little fluctuation; therefore, no sensitivity cases were run. However, higher ambient temperatures and surface temperatures should generally produce lower gas concentrations and downwind dispersion distances.

None of the trials had experimental ambient pressures that differed by more than 10 percent from atmospheric pressure but in order to gauge the sensitivity, the Burro and Coyote trials, which had the lowest ambient pressures, were tested. Higher ambient pressure showed lower concentrations and downwind dispersion distances for the Burro 8 and Coyote 3 trials, but for the Burro 9 trial, the effect was very low or negligible. Although alternative atmospheric pressure conditions are not specified in 49 C.F.R. § 193.2059, it is recommended that atmospheric pressure be specified in the siting package.

Phast version 8.4 must be used in accordance with 49 C.F.R. § 193.2059, which requires the dispersion conditions are a combination of those that result in longer predicted downwind dispersion distances than other weather conditions at the site at least 90 percent of the time, or alternative conditions with a wind speed of 4.5 miles per hour (2.01 m/s) at reference height of 10 meters; an Atmospheric Stability (Pasquill-Gifford Class) of F; relative humidity of 50 percent; and average temperature of the region for models that result in longer predicted downwind dispersion distances at lower wind speeds. The F stability prescribed in 49 C.F.R. § 193.2059 generally provides reasonable, or conservative, results for LNG releases that disperse over land or water. The weather conditions reflective of the site should be included with siting package for use in vapor-gas dispersion exclusion zone calculations, including the lowest wind data in the area. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst-case results.

The sensitivity analysis of the substrate indicated a moderate effect for all cases. The substrate resulted in variable behavior among the trials where a change to a shallow pool for the Maplin Sands 27 trial caused a decrease in concentration, and a change to a deep pool for the other trials resulted in a decrease in concentration for the Burro 8 trial and increase for the Burro 9 and Coyote 3 trials. The input parameters, including the specification of the substrate, should be included with the siting package for use in exclusion zone calculations.

The LNG trials considered in this evaluation were spills on water, which require a different source term compared to spills on land. The source term for a spill on water is fairly steady due to the nearly constant heat transfer from the water to the LNG from convective motion and thermal mass of the water. This contrasts to spills on land where the source term will be initially high then decrease due to conductive cooling between the LNG and land. Pressurized releases will also provide different source terms compared to releases on water. Any source term model that is used to calculate an exclusion zone for an LNG facility must have a suitable basis to comply with the siting requirements in 49 C.F.R. Part 193.[10] Therefore, for spills over land and pressurized releases, it is recommended that the source term be evaluated before usage.

An increase in molecular weight resulted in a decrease in concentration for all the trials except for the Maplin Sands 27 trial where it increased. Although the composition specified in the MEP 2016 reflects the composition of the LNG, methane makes up the primary component of LNG and is the initial species to preferentially boiloff from the pool. Thus, the molecular weight of methane is recommended in the MEP 2016 to be used to reflect preferential boiloff, which was used for all base cases.

Overall, the sensitivity analysis showed that concentrations generally differ by less than a factor of two from the base case and the downwind dispersion distances to the LFL differ by less than a factor of two. Consequently, Phast version 8.4 must be used with a safety factor of two due to the results of the sensitivity analysis and to compensate for uncertainties related to potential turbulent fluctuations, source term specification, wind tunnel experiment validation results, dispersion over water, and low wind speed and high atmospheric stability validation results.

[10] In the Matter of Mssrs. Keppel and Miozza, PHMSA Interp. (Jul. 7, 2010); In the Matter of Fulbright & Jaworski L.L.P., PHMSA Interp. #PI 10-0005 (available at www.phmsa.dot.gov).

Comparison of MEP Results from Phast version 6.6 and 8.4

In comparing the performance of Phast version 8.4 to version 6.6[11] it should be noted that Phast version 6.6 was evaluated using the MEP version 11, whereas Phast version 8.4 was evaluated using MEP version 12. The updated MEP version 12 includes numerous changes which do not allow for an equivalent comparison between the statistical performance measures for both versions of Phast. Some of the major changes to the MEP include:

- The maximum arc-wise concentration is taken to be the maximum at any sensor elevation location on an arc that is applied to measured and predicted values. Previously the maximum arc-wise concentration was evaluated from sensors at a single elevation nearest to the ground on an arc.
- Concentrations less than or equal to 0.1 percent are included whereas previously they were excluded.
- Ten data points for the field trials have been added.
- Point concentrations are included for the Maplin Sands and Thorney Island trials whereas previously only maximum arc-wise concentrations were provided.
- For Burro 8, the averaging window for long time averages were corrected for sensors at the 57 m arc and for three sensors at the 400 m arc.

Despite these changes, the comparison of the SPM values for long time averages provided in Table 12 indicates only two SPMs result in worse performance for version 8.4 compared to version 6.6. These include the maximum arc-wise and point-wise concentration for SPM FAC2. However, better performance results for SPM MRB and SPM CSF for point-wise concentration. With regards to the SPM values for short time averages, Table 13 indicates version 8.4 results in worse performance for SPMs of MRB, MG, and VG. This performance can be attributed to the inclusion of the Maplin Sands trials which when removed results in all SPM criteria being met by version 8.4. Regarding point-wise concentration, the SMP values for short time averages are provided in Table 14. Since version 6.6 does not include point-wise data for Maplin Sands a comparison is provided to version 8.4 with the Maplin Sands trials removed. Both versions of Phast meet all SPM criteria.

For long time averages, the comparison of SPM values indicates that version 8.4 does not perform worse overall than version 6.6. This is also true of short time average SPM values if the Maplin Sands trials are removed, which given the differences between MEP versions 11 and 12, provides the most equivalent comparison.

Table 12: MEP Statistical Performance Measures for Phast version 6.6 and 8.4
Long time averages

[11] On October 7, 2011, PHMSA issued a Final Decision approving Phast versions 6.6 and 6.7. There are no significant differences between versions 6.6 and 6.7 in terms of consequence results.

SPM	Maximum arc-wise concentration		Distance to maximum arc-wise concentration		Point-wise concentration		Cloud width	
long time averages	**v. 6.6**	**v. 8.4**	**v. 6.6**	**v. 8.4**	**v. 6.6**	**v. 8.4**	**v. 6.6**	**v. 8.4**
-0.4 < MRB < 0.4	-0.12	0.29	-0.04	0.14	-0.41	0.36	0.05	0.01
MRSE < 2.3	0.35	0.67	0.22	0.25	0.72	0.77	0.15	0.14
0.67 < MG < 1.5	0.88	1.38	0.97	1.15	0.60	1.45	1.04	0.98
VG < 3.3	1.48	2.28	1.29	1.32	3.27	2.84	1.19	1.21
0.5 < FAC2	0.74	0.39	0.87	0.73	0.55	0.4	0.90	0.95
0.5 < CSF < 2	1.36	1.06	1.15	Na	3.01	1.24	1.07	na

Red colored entry indicates criteria was not met.

Table 13: MEP Statistical Performance Measures for Phast version 6.6 and 8.4 Short time averages

SPM	Maximum arc-wise concentration			Distance to max arc-wise concentration		
short time averages	**v. 6.6**	**v. 8.4**	**V 8.4 (without Maplin Sands)**	**v. 6.6**	**v. 8.4**	**V 8.4 (without Maplin Sands)**
-0.4 < MRB < 0.4	0.36	0.49	0.07	0.29	-0.01	-0.04
MRSE < 2.3	0.44	1.06	0.49	0.31	0.13	0.12
0.67 < MG < 1.5	1.50	2.24	1.12	1.37	0.99	0.97
VG < 3.3	1.75	15.37	1.97	1.46	1.15	1.14
0.5 < FAC2	0.67	0.50	0.69	0.82	0.93	0.92
0.5 < CSF < 2	0.79	0.85	1.15	na	na	1.10
0.5 < CSF_LFL < 2	0.79	1.25	1.40	na	na	na

Red colored entry indicates criteria was not met.

Table 14: MEP Statistical Performance Measures for Phast version 6.6 and 8.4 Short time averages

SPM	Point-wise concentration	
short time averages	**v. 6.6**	**v. 8.4**
-0.4 < MRB < 0.4	0.00	-0.06
MRSE < 2.3	0.36	0.58
0.67 < MG < 1.5	0.99	0.93
VG < 3.3	1.67	2.32
0.5 < FAC2	0.78	0.59
0.5 < CSF < 2	1.44	1.71

In addition to comparing SPM values, Table 15 provides a comparison between version 6.6 and 8.4 of calculated distances to the LFL defined as a concentration of 4.4 percent v/v. The LFL values were evaluated at a concentration level of 4.4 percent v/v for version 6.6 instead of 5 percent, the reason for which is unknown. Thus, DNV was asked to provide distances at a concentration of 4.4 percent v/v using version 8.4 to provide an equivalent comparison. Table 15 indicates that for short time averages the distances increase an average of 34 percent and 28 percent to the LFL and ½ LFL, respectively, for all trials expect for Burro 8 where distances decreased about 14 percent and 23 percent to the LFL and ½ LFL, respectively. Thus, overall, the use of Phast version 8.4 will result in further distances to the LFL and ½ LFL compared to version 6.6, thereby providing more conservative results. However, the results also indicate that very stable, low wind speed conditions provide reduced distances to the LFL and ½ LFL using version 8.4. This is consistent with the outlier behavior regarding Burro 8 as mentioned previously pertaining to predicted distances to the LFL and ½ LFL. Burro 8 short is an experiment carried out under low wind and stable atmospheric conditions. DNV is not fully certain why Phast v8.4 underpredicts the distances to the LFL for the Burro 8 experiment. DNV believes that there may be some imprecision in the results. More importantly, Burro 8 has a windspeed of less than 2 m/s, and fairly stable (E) conditions, and very low windspeeds for clouds dispersing over pools can give rise to problems—dispersing observers can become almost stationary in the presence of the evaporating pool (i.e. adding large amounts of mass rates with zero horizontal momentum). Nonetheless, it is noteworthy that agreement with experiment is as good or better overall for Phast v8.4 than Phast v6.7 (pointwise MG = 1.06 vs 1.05; arcwise MG = 2.24 vs 2.4). Thus, it is recommended that at least a distance uncertainty factor of two is used for short time averages, which is more appropriate for predicting flammable regions.

Table 15: Distances to LFL and ½ LFL for Phast version 6.6 and 8.4 (LFL defined as 4.4% v/v concentration for comparison)						
	Version 6.6		**Version 8.4**		**Percent difference (%)**	
Trial - stability, wind speed (m/s)	**LFL (m)**	**1/2 LFL (m)**	**LFL (m)**	**1/2 LFL (m)**		
Maplin Sands 27 - C/D, 5.5	95.8	150.5	121.7	182.6	27.0	21.3
Maplin Sands 34 – D, 8.6	106	163.9	147.3	219.8	39.0	34.1
Maplin Sands 35 – D, 9.8	105.2	164	147.1	220.4	39.8	34.4
Burro 3 Long – C, 5.58	225	300.7	301.1	386.1	33.8	28.4
Burro 3 short – C, 5.58	256	345.1	303.0	392.0	18.4	13.6
Burro 7 long – D, 8.75	237	337.3	319.8	430.7	34.9	27.7
Burro 7 short – D, 8.75	282	399	322.8	441.7	14.5	10.7
Burro 8 long – E, 1.94	175	331.2	206.5	343.2	18.0	3.6
Burro 8 short – E, 1.94	242	447.9	207.1	346.8	-14.4	-22.6
Burro 9 long – D, 5.94	280	389.5	431.9	581.2	54.3	49.2
Burro 9 short – D, 5.94	375	528.1	433.5	587.0	15.6	11.2
Coyote 3 long – C, 6.77	232	308.6	346.9	445.7	49.5	44.4
Coyote 3 short – C, 6.77	250	336.2	348.2	449.8	39.3	33.8
Coyote 5 long – C, 10.47	250	334.2	357.5	462.1	43.0	38.3
Coyote 5 short- C, 10.47	270	363.2	360.4	470.7	33.5	29.6
Coyote 6 long – D, 5.04	245	363.3	387.1	522.8	58.0	43.9
Coyote 6 short – D, 5.04	296	447.1	389.4	531.2	31.6	18.8

Red colored entry indicates distance decreased using version 8.4, while green indicates an increase