



U.S. Department
of Transportation

**Pipeline and Hazardous
Materials Safety
Administration**

Administrator

1200 New Jersey Avenue SE
Washington, DC 20590

OCT - 7 2011

Mr. Filippo Gavelli, Ph.D.
Head of Dispersion Consulting
GexCon US Inc.
7735 Old Georgetown Road
Suite 1010
Bethesda, MD 20814

Re: PHMSA Docket No. 2011-0101

Dear Dr. Gavelli:

Enclosed please find a Final Decision on your petition for approval of the FLACS (Version 9.1 Release 2) vapor gas dispersion model. Service of this Final Decision by UPS Overnight Express is deemed effective upon the date of mailing, or as otherwise provided under 49 C.F.R. § 190.5.

Thank you for your cooperation in this matter.

Regards,

Cynthia L. Quarterman

Enclosure

UPS OVERNIGHT EXPRESS - RETURN RECEIPT REQUESTED

**U.S. DEPARTMENT OF TRANSPORTATION
PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION
OFFICE OF PIPELINE SAFETY
WASHINGTON, D.C. 20590**

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In the Matter of)	
)	
GexCon US Inc.,)	PHMSA Docket No. 2011-0101
)	
Petitioner.)	
)	

FINAL DECISION

GexCon US Inc. (Petitioner or GexCon) has filed a petition for approval (Petition) of FLACS¹ (Version 9.1 Release 2) under 49 C.F.R. §§ 190.9 and 193.2059(a).² On August 15, 2011, the Pipeline and Hazardous Materials Safety Administration (PHMSA) issued a Draft Decision proposing to approve the Petition and providing the public with a 30-day comment period. After reviewing those comments and making certain modifications to the determinations in the Draft Decision, PHMSA is approving the Petition in this Final Decision.

Procedural History

On October 27, 2010, GexCon submitted this Petition for approval of the FLACS vapor gas dispersion model. As suggested in an August 30, 2010 PHMSA advisory bulletin, the Petition included general information on vapor gas dispersion modeling and specific information about the history and capabilities of FLACS. It also included a partially-completed Model Evaluation Report with information on the suitability of FLACS as demonstrated under the three-stage Model Evaluation Protocol (MEP). By letters dated December 3 and 7, 2010, GexCon supplemented its Petition by submitting the remaining portions of the Model Evaluation Report (MER) for FLACS. PHMSA received the data associated with GexCon's submission on December 22, 2010.

On April 22, 2011, PHMSA sent GexCon a written request for additional information. After additional consultation with PHMSA and the Federal Energy Regulatory Commission (FERC), GexCon submitted the requested information on June 3, 2011.

¹ FLACS was originally named the FLame ACceleration Simulator.

² The electronic docket for this Petition is available at <http://www.regulations.gov/#!searchResults;rpp=10;po=0;s=PHMSA+2011-0101>.

On August 15, 2011, PHMSA issued a Draft Decision proposing to approve the Petition and providing the public with a 30-day comment period. PHMSA also published a Notice in the Federal Register on September 1, 2011, stating that the Draft Decision was available for public inspection.³

Two parties offered comments: GexCon US Inc., and Hess LNG. GexCon's comments, submitted by letter dated September 7, 2011, focused on twelve aspects of the Draft Decision: (1) clarification on the ability to model dispersion from horizontally or vertically oriented releases; (2) limitation on the ability to model dispersion from releases that disperse over terrain with a 10% or greater grade; (3) clarification on compressible URANS solver on simulation time; (4) clarification on substances that can be specified; (5) clarification on JET utility model; (6) clarification on the need to align the grid with the release direction; (7) clarification on the pool sub-model; (8) clarification on the ability to model dispersion with zero wind speed; (9) clarification of the performance of FLACS against MEP quantitative acceptance criteria for obstructed field trials; (10) clarification on the quantification of experimental uncertainty for field trials; (11) clarification of separate utilities and sub-models; and (12) the active and planned development for future releases. Hess LNG's comments, submitted by letter dated September 9, 2011, focused on three aspects of the Draft Decision: (1) clarification on the acceptance of the source terms included with and within the FLACS model; (2) clarification on the ability to model dispersion from releases that disperse over terrain with a 10% or greater grade; and (3) clarification on the ability to model dispersion from horizontally or vertically oriented releases.

Background

PHMSA issues federal safety standards for siting LNG facilities.⁴ Those standards require that an operator or a governmental authority exercise control over the activities that can occur within an "exclusion zone," defined as the area around an LNG facility that could be exposed to unsafe levels of thermal radiation or flammable vapor gas in the event of a release or ignition.⁵ PHMSA also requires that certain mathematical models be used to calculate the dimensions of these exclusion zones.⁶

Under the current regulations, vapor-gas-dispersion exclusion zones may be calculated using either the DEGADIS Dense Gas Dispersion Model (DEGADIS) or FEM3A.⁷ The Administrator

³ Pipeline Safety: Issuance of Draft Decision on GexCon US, Inc. Petition for Approval of Flame Acceleration Simulator, 76 Fed. Reg. 54533 (Sept. 1, 2011).

⁴ Pipeline Safety Act of 1979, Pub. L. No. 96-129, § 152, 93 Stat. 989 (1979) (currently codified at 49 U.S.C. § 60103(a)).

⁵ 49 C.F.R. § 193.2007 (defining exclusion zone).

⁶ 49 C.F.R. §§ 193.2057-2059.

⁷ Liquefied Natural Gas Regulations—Miscellaneous Amendments, 62 Fed. Reg. 8402 (Feb. 25, 1997) (incorporating "the model described in the Gas Research Institute Report GRI-89/0242 . . . , 'LNG Vapor Dispersion Prediction with the DEGADIS Dense Gas Dispersion Model.'"); Pipeline Safety: Incorporation of Standard NFPA

may also approve the use of alternative vapor-gas dispersion models that “take into account the same physical factors and have been validated by experimental test data.”⁸

On August 30, 2010, PHMSA issued an Advisory Bulletin with guidance on obtaining approval of alternative vapor gas dispersion models.⁹ The Advisory Bulletin stated that a petitioner could seek the Administrator’s approval of an alternative vapor gas model by following the three-stage Model Evaluation Protocol (MEP) and submitting a Model Evaluation Report (MER) with satisfactory information about the proposed model.¹⁰ As the Advisory Bulletin explained:

The MEP is based on three distinct phases: scientific assessment, model verification and model validation. The scientific assessment is carried out by obtaining detailed information on a model from its current developer using a specifically designed questionnaire and with the aid of other papers, reports and user guides. The scientific assessment examines the various aspects of a model including its physical, mathematical and numerical basis, as well as user oriented aspects. . . . The outcome of this scientific assessment is recorded in a[n] [MER] . . . , along with the outcomes of the verification and validation stages. . . .

[In] [t]he verification stage of the protocol[,] . . . evidence . . . is sought from the model developer and this is then assessed and reported in the MER. The validation stage of the MEP involves applying the model against a database of experimental test cases including both wind tunnel experiments and large-scale field trials. The aim of the validation stage is . . . to quantify the performance of a model by comparison of its predictions with measurements.¹¹

59A in the Liquefied Natural Gas Regulations 65 Fed. Reg. 10950 (March 1, 2000) (incorporating FEM3A “to account for additional cloud dilution which may be caused by the complex flow patterns induced by tank and dike structure.”).

⁸ 49 C.F.R. §§ 193.2057(a), 193.2059(a); *see also* 49 C.F.R. § 190.11 (2010) (authorizing the submission of petition for finding or approval with the Administrator).

⁹ Liquefied Natural Gas Facilities: Obtaining Approval of Alternative Vapor-Gas Dispersion Models, 75 Fed. Reg. 53371-53374 (Aug. 31, 2010).

¹⁰ An industry-commissioned panel of experts in the field of consequence modeling developed the MEP and MER in the late 2000s. M.J. Iving et al., *Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities Research Project: Technical Report* (Apr. 2007) (available at www.nfpa.org) (Original FPRF Report), and supplemented in S. Coldrick et al., *Validation Database for Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities: Guide to the LNG Model Validation Database, Version 11.0* (May 2010) (available at www.nfpa.org) (Supplemental FPRF Report). A PHMSA-commissioned panel of experts performed an independent review of the MEP and produced a separate technical report, National Association of State Fire Marshals, *Review of the LNG Vapor Dispersion Model Evaluation Protocol* (Jan. 2009) (NASFM MEP Report); *see also* National Association of State Fire Marshals, *Review of the LNG Source Term Models for Hazard Analysis: A Review of the State-of-the-Art and an Approach to Model Assessment* (Jun. 2009) (NASFM Source Term Report).

¹¹ 75 Fed. Reg. at 53372.

The Advisory Bulletin further stated that a petitioner should consider addressing other concerns in completing the MEP and MER; that the guidance it contained was not binding and may require modification or clarification in appropriate cases; and that a petitioner could seek the Administrator's approval of an alternative vapor gas dispersion model by any other appropriate means.

Analysis¹²

Evaluating the suitability of an alternative vapor gas dispersion model is a task that involves "making predictions, within [PHMSA's] area of special expertise."¹³ The Advisory Bulletin provided interested parties with guidance on obtaining approval of an alternative vapor gas dispersion model under 49 C.F.R. § 193.2059(a), and GexCon adhered to that guidance in preparing this Petition, i.e., it subjected FLACS to the MEP and submitted an MER with detailed information about its model, including the results of the scientific assessment, verification, and validation.

In the Draft Decision, PHMSA noted that it had reviewed the information submitted by GexCon and determined that FLACS could be used to calculate the vapor gas dispersion exclusion zone for an LNG facility in certain scenarios. PHMSA also asked the public to comment on its determinations.

Response to Public Comments

GexCon submitted comments on twelve aspects of the Draft Decision. First, GexCon commented that FLACS is able to model dispersion from a release in any direction, and is not limited to just horizontal and vertical releases. For the applications pertinent to this study, most releases would be oriented vertically or horizontally. It was not the intent to limit the model to those scenarios; therefore, PHMSA has clarified that FLACS is able to model dispersion from a release in any direction (horizontally, vertically, or otherwise) in the Final Decision.

GexCon's second comment argues that the limitation of the ability to model dispersion from releases with a 10% or greater grade can be reduced by: (1) modeling an upward slope as a flat or lesser upward slope; (2) modeling the slope with a reduction in vertical grid size; or (3) modeling the slope with a modified gravity vector. PHMSA agrees that assuming an upward slope as a flat or lesser upward slope would be conservative, and has provided clarification that FLACS may be used in this manner. As stated in the Draft Decision, PHMSA agrees that grid refinement may reduce the error associated with the Cartesian grid when modeling sloped terrain; however, this effect has not been quantified and, therefore, as stated in the Draft

¹² This analysis relates solely to the use of FLACS for the purpose of complying with the specific requirements of 49 C.F.R. Part 193 and is not intended authorize or restrict its use in any other applications.

¹³ *Baltimore Gas and Electric Company v. Natural Resources Defense Council*, 462 U.S. 87, 103 (1983); see *Wisconsin Electric Power Company v. Costle*, 715 F.2d 323, 329 (7th Cir. 1983) (upholding EPA's use of a particular dispersion model and stating that its "choice to rely on an air quality model is a policy judgment deserving great deference."); *Howmet Corp. v. E.P.A.*, 614 F.3d 544, 549 (D.C. Cir. 2010) (describing strong level of deference owed to agency in administering technically complex regulations).

Decision, FLACS may not be appropriate for modeling dispersion along undulating terrain or slopes through modification of the geometry, which may be influenced by the Cartesian grid stepping. As stated in the Draft Decision, PHMSA also agrees that a slope may be modeled by adjusting the gravity vector, as was done in the validation study. However, this approach is limited to slopes with a 10% or less grade. This is based on the validation of the FLACS model using the modified gravity vector approach, which showed a divergent trend with increasing downward slope that eclipsed the recommended safety factor of 2 at 11.6% grade. For that reason, FLACS is limited to model slopes with a 10% or less grade until it can be demonstrated that using the modified gravity vector approach for steeper grades does not cause a further divergence from the recommended safety factor of 2. In addition, FLACS is limited to model slopes with a 10% or less grade using the modified gravity vector approach until it can be demonstrated that using the stepped geometry approach does not cause a divergence from the recommended safety factor of 2.

GexCon's third comment requests that the term "unnecessary" be removed when describing the increase in simulation time caused by solving for compressible flow and a URANS turbulent closure model. GexCon argues that LNG spills into impoundments and trenches will not have a steady state solution due to the transient nature of the pool spreading and of the heat transfer from the ground. GexCon argues that in those cases, using a steady state model would result in physically inaccurate results.

As stated in the Draft Decision, using an incompressible solver will reduce computation times for dispersion simulations without significantly affecting the dispersion results. This has also been recognized by GexCon (as is evident by the active development of an incompressible solver for dispersion simulations). However, as stated in the Draft Decision, PHMSA also agrees that using a compressible and unsteady solver is more scientifically accurate and that steady state solutions may not exist for many cases pertinent to 49 C.F.R. § 193.2059 applications. Therefore, PHMSA has removed the word "unnecessary" and has provided additional clarification in the Final Decision.

GexCon's fourth comment clarifies that a user may define any substance by defining the physical and thermal properties of that substance. PHMSA agrees and has clarified this in the Final Decision.

GexCon's fifth comment clarifies that JET utility model is a separate model that is intended to model choked flow of gaseous jet sources. PHMSA has clarified this in the Final Decision.

Similar to GexCon's first comment, the sixth comment clarifies that jet source axis does not need to be aligned with the Cartesian mesh. However, GexCon does recognize that a jet aligned with one of the major axes is preferable and that grid refinement in all three directions may be necessary in addition to a more careful examination of the release behavior. PHMSA has clarified this in the Final Decision.

GexCon commented that the pool sub-model is not separate from FLACS and is able to simulate the spreading and vaporization of any material in the FLACS database, as well as any material

specified by the user through the USERSPEC option. PHMSA has clarified this in the Final Decision.

GexCon's next comment requested that PHMSA clarify that FLACS can model dispersion without the presence of wind. This was not included in the Draft Decision, since it typically has little relevance to the weather condition that produces that longest dispersion distance. However, PHMSA has clarified this in the Final Decision.

GexCon's ninth comment was a request that PHMSA clarify that FLACS did meet the MEP quantitative acceptance criteria for all trials, including obstructed wind tunnel tests, and the only exception was for obstructed field trials. This is only partially correct. PHMSA agrees that FLACS meets the MEP quantitative acceptance criteria for maximum arc-wise concentrations for scaled obstructed wind tunnel tests. PHMSA also agrees that FLACS does not meet the MEP quantitative acceptance criteria for maximum arc-wise concentrations for obstructed field trials with short time averages. However, as shown in Table 1, FLACS does not meet the MEP quantitative acceptance criteria for maximum arc-wise concentrations for obstructed tests with long time averages, which is a mean of both un-scaled obstructed wind tunnel tests with long time averages and obstructed field trials with long time averages. Similar trends are shown for maximum gas concentration arc-wise distances. In addition, FLACS does not meet the MEP quantitative acceptance criteria for maximum arc-wise concentrations for unobstructed field trials with short or long time averages for the geometric variance, nor does FLACS meet many of the MEP quantitative acceptance criteria for maximum point-wise gas concentrations with similar trends for the prediction of cloud widths. PHMSA has clarified this in the Final Decision. The MEP specific performance measures and quantitative acceptance criteria are based on various averages of field trials and wind tunnel tests, which can be misleading. Therefore, the Advisory Bulletin required the specific performance measures (SPMs) for all tests to allow for better examination of trends among the tests.

GexCon's tenth comment requested that PHMSA provide additional discussion of the possible uncertainties in the experimental data for the field trials. The Petitioner agrees that examination of model predictions against individual experiments can provide additional useful insight into a model's performance, but argues that there has not been sufficient consideration given to the experimental uncertainty from unknown events, such as wind gusts, solar radiation, small vegetation, etc. The Petitioner argues that these unknown events are even more prevalent for field trials.

As stated in the Advisory Bulletin, Section 6.2 Evaluation Against MEP Quantitative Assessment Criteria, PHMSA requested that the Petitioner provide an uncertainty analysis that accounts for experimental uncertainty due to sensor measurement with the option to examine additional sources of uncertainty, including sampling time, averaging time, spatial/volumetric averaging, cloud meander, and any other error associated with the experiment. Information for the majority of the experimental trials is publically available, including the majority of the field trials (Burro, Coyote, Falcon). The publically available reports contain information and data on the sensors and test conditions, including wind sensors, radiometers, terrain, etc. As stated in the Advisory Bulletin, this information was not required to be quantified; however, this information could have been leveraged to provide more realistic inputs into a model (i.e., fewer assumptions

and simplifications) or provide a better explanation of the deviation in the model predictions. PHMSA recognizes that GexCon took advantage of some of this data to account for more realistic (i.e., transient) wind velocities in some of the trials to allow for better model predictions. As recognized in the Draft Decision, the deviation between the experimental conditions and model setup conditions accounts for a portion of the deviation from the experimental data. As explained in the Draft Decision, the largest impact from these deviations is for predictions of maximum point-wise gas concentrations. PHMSA has considered these effects when determining the recommended safety factor.

Similar to previous comments, GexCon's eleventh comment recommended clarification on which models were separate utilities and which were built-in sub-models. PHMSA has clarified this in the Final Decision.

GexCon's final comment summarized the active and planned development for future releases. PHMSA recognizes that many of these developments will improve the computational time and accuracy of the model, and welcomes additional advances in the scientific modeling community.

Hess LNG's first comment requested that PHMSA indicate whether or not the JET and FLASH utilities included with FLACS and the pool spread sub-model within FLACS are acceptable for use for determining dispersion distances under 49 C.F.R. Part 193. As stated in the Draft and Final Decisions, the specification of the source term is a key parameter in determining the gas concentrations and dispersion distances. The Draft and Final Decisions provide limitations of the dispersion model where the assumptions within a source term model have a direct impact on the dispersion distance results. 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. The suitability of the source term model will depend on the release scenario being examined and the source term model basis. The MEP evaluates the scientific basis of the dispersion model and the experimental trials within the validation database are not representative of all exclusion zone scenarios. Subsequently, the source term model was not evaluated under the MEP or the Advisory Bulletin, and any source term model and assumptions used in the exclusion zone calculations should be described, and should include all input and output files.

Hess LNG's second comment requested clarification on the ability to model dispersion from releases that disperse over terrain with obstructions that may have 10% or greater slopes, such as berms. As stated in the Draft Decision, FLACS has demonstrated that it is able to predict maximum arc-wise concentrations for releases that disperse over obstructions, such as vapor fences. PHMSA expects that the ability of FLACS to model dispersion over obstructions with sloped surfaces that span short distances would be more comparable to dispersion over obstructions than it would be to dispersion over terrain with sloped surfaces that span long distances. PHMSA agrees that berms and features of these types are more suitably classed as obstructions than sloped surfaces. PHMSA has clarified this in the Final Decision.

Hess LNG's last comment requested clarification on the ability to model dispersion from horizontally or vertically oriented releases—similar to GexCon's first comment. As previously mentioned, FLACS is able to model dispersion from a release in any direction, and is not limited to just horizontal and vertical releases. For the applications pertinent to this study, most releases

would be oriented vertically or horizontally, and it was not the intent to limit the model to those scenarios. Therefore, PHMSA has clarified that FLACS is able to model dispersion from a release in any direction (horizontally, vertically, or otherwise) in the Final Decision.

Other Issues

PHMSA noticed during additional review of the Draft Decision that further clarification may be needed in the following areas.

The stated limitations in the beginning of the Draft Decision did not include the recommended safety factor necessary to compensate for model uncertainty or the statement regarding the conservative nature of the ambient conditions required per 49 C.F.R. § 193.2059 as was stated at the end of the Draft Decision. These statements have been included in both locations in the Final Decision.

The term “aspect ratio” is intended to represent the ratio of the length of the source term relative to the width of the source term (e.g., ratio of the surface dimensions of the impoundment), and is not intended to represent the ratio of the length or width relative to the depth of an impoundment. Therefore, sources with high aspect ratios would include long trenches or channeled liquid flow, while low aspect ratio would include square and most rectangular impoundments or radial liquid flow. The spill containment layout and pool spread calculations should be included with model submissions for use in exclusion zone calculations.

The term “sloped terrain” is not intended to prohibit dispersion over upward slopes or moderately graded slopes. Site grade information should be included with model submissions for use in exclusion zone calculations. PHMSA has clarified this in the final decision.

This document also provides additional clarifications and information that should be included with model submissions for use in exclusion zone calculations.

Summary of Findings, Limitations, and Conclusions

FLACS may be used to model the maximum arc-wise concentration for:

- Dispersion from circularly- and irregularly-shaped LNG pools;
- Dispersion from LNG pools with low- and high-aspect ratios (ratio of the surface dimensions of the impoundment), including impoundments and trenches;
- Dispersion from releases in any direction (horizontal, vertical, or otherwise), including releases from flashing, venting, vent stacks, and pressure relief discharge;
- Dispersion from multiple coincident releases, including multiple release locations that may influence each other;

- Dispersion over sloped terrain with a 10% or less grade; and
- Dispersion over obstructions, including large obstructions that may cause wind-channeling and obstructions that may reduce the momentum and subsequent mixing of a high pressure release.

In some cases, FLACS may not be appropriate to be used to model the maximum arc-wise concentration for:

- Dispersion under unstable atmospheric (i.e., A, B, C) stability conditions;
- Dispersion under low ambient pressure (i.e., less than 90 kPa) conditions; or
- Dispersion over varying or sloped terrain with a 10% or greater grade.

The ambient conditions required under 49 C.F.R. § 193.2059 should produce conservative results (i.e., higher downwind gas concentrations and dispersion distances), and therefore PHMSA does not consider the limitation for unstable atmospheric stability conditions and low ambient pressure a limitation for 49 C.F.R. § 193.2059 applications.

The omission of upward slopes or sloped obstructions that span short distances (e.g., berms, swells, etc.) should provide conservative results (i.e., higher downwind gas concentrations and dispersion distances), and therefore is not considered as a limitation for 49 C.F.R. § 193.2059 applications. The inclusion of sloped obstructions that span short distances (e.g., berms, swells, etc.) would be more representative of the validation against obstructions and would not be limited to slopes of 10% or greater.

FLACS should be used with a safety factor of 2 (i.e., ½ LFL) to compensate for uncertainties related to potential turbulent fluctuations, source term specification, wind tunnel experiment validation results, obstructed validation results, sloped validation results, and atmospheric stability validation results.

Scientific Assessment

FLACS is a computational fluid dynamics (CFD) model developed by GexCon. FLACS has been developed for predicting the fluid dynamics associated with dispersion and combustion of flammable liquids, gases, and dusts clouds in realistic geometries. FLACS is capable of simulating the dispersion of steady or unsteady releases in both the passive and dense gas regime. FLACS is primarily a dispersion model and deflagration model with separate models for flashing and jetting and a sub-model for liquid pool spread.

FLACS solves the compressible Navier-Stokes governing equations for mass and momentum using the unsteady Reynolds Averaged Navier-Stokes (URANS) approach, in which the fluid velocity is separated into Reynolds averaged and turbulent fluctuating components.

Currently, there is not an option to switch to an incompressible model or to a steady state model. Although solving the compressible equations is necessary for deflagration simulations, it may

increase simulation times for scenarios where compressibility is often not relevant (i.e., pool spread and dispersion) without a noticeable increase in solution accuracy. Solving the URANS equations may also increase simulation times for steady state simulations. However, for applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which examines 10-minute releases that often would not be characteristic of a steady state release due to the transient nature of flow and heat transfer. Although using these approaches increases simulation time, solving for compressible and unsteady flow is more scientifically accurate.

The turbulent fluctuations are taken into account in FLACS by calculating the generation and dissipation of turbulent kinetic energy (TKE) using a two-equation standard k-epsilon turbulence model, including modifications for the following: generation of turbulence behind sub-grid objects; build-up of turbulence behind objects of a size for which the discretization produces too little turbulence; buoyancy generated turbulence; turbulence calculated from Pasquill-Gifford class for inflow; and turbulent wall functions. The commonly used two-equation, k-epsilon turbulence model has some known deficiencies, such as its inability to predict counter-gradient diffusion. However, this is generally not a concern for use in calculations required by 49 C.F.R. § 193.2059. The k-epsilon model is commonly used in CFD models and has a relatively low computational cost and high degree of robustness compared to other turbulence closure models. Use of this turbulence model in FLACS is not expected to be a significant source of uncertainty for purposes of the calculations required by 49 C.F.R. § 193.2059.

Spatial discretization

FLACS uses a finite-volume approach on a hexahedral 3D Cartesian grid to discretize the domain (i.e., study area) into control volumes (CV) over which it solves the URANS equations. FLACS is not capable of automatic mesh generation or refinement; grid generation and refinement must be done manually. The user documentation provides general guidelines for mesh resolution. Sub-grid objects are resolved using a Porosity-Distributed Resistance (PDR) methodology that calculates flow resistance terms, turbulence generation/source terms, and flame acceleration terms based on flame wrinkling/folding in the sub-grid wake. The flame folding parameter is important for explosion calculations, but irrelevant for pure dispersion calculations. FLACS uses different drag coefficients for cylindrical and rectangular sub-grid objects, and significant drag and turbulence are generated only behind an object, not along an object that partly blocks a CV. This greatly reduces the computational time for simulations where a large number of objects (i.e., congestion) exist in the flow field. The PDR methodology allows FLACS to provide faster simulations than other CFD packages that try to represent and resolve objects in the grid. Although the PDR methodology is used at the cost of some accuracy, it allows for more accurate results than ignoring the objects (i.e., assuming unobstructed flow). However, the structured grid and PDR may cause some inaccuracies when modeling curved or sloped surfaces. Sloping terrain may be approximated by changing the gravity vector direction. However, approximations of undulating geometries or sloped surfaces relative to the gravity vector will result in a stepped Cartesian mesh with varying porosity values. This may introduce artificial obstructions and restrict flow along upward slopes and introduce artificial turbulent mixing and dilution along downward slopes. Although grid refinement will reduce some of these errors, the porosity calculations may influence the results when the grids are translated or their size and shape are changed. If an object does not span an entire grid or does not align with

the grid, porous gaps may be modeled instead of a closed surface (i.e., solid boundary). Conflicts may also occur where two objects of different geometry are located within the same grid (sub grid scale). For this reason, the user must verify that closed surfaces or corners remain closed within the grid and that openings in walls remain open within the grid. This may be done by visually confirming the porosity values in Flowvis and adjusting the grid or object to create a solid boundary. In general, PHMSA recommends that grid sensitivity analyses be conducted for CFD modeling to demonstrate a grid independent result or convergence to a grid independent result.

Numerical solver

FLACS numerically solves the URANS partial differential equations for compressible flow using the Semi Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm and employs a stabilized biconjugate gradient (BICGSTAB) solver. FLACS uses a non-Boussinesq approach in which variations in fluid density are included throughout the governing equations. Kappa schemes with weighting between second-order upwind and central differencing schemes (delimiters for some equations) are utilized for spatial discretization to solve the conservation equations for mass, impulse, enthalpy, turbulence, and species/combustion. A first-order accurate, backward Euler time differencing scheme and a combination of first- and second-order accurate temporal discretization schemes are used. However, for the reaction progress variable, the second-order accurate van Leer scheme is used to prevent artificial flame thickening caused by numerical diffusion. This is important for explosion calculations, but irrelevant for pure dispersion calculations. Other schemes may provide quicker simulation results compared to the SIMPLE algorithm, which solves for the pressure gradient term using the pressure distribution in an iterative process (BICGSTAB). Although using these approaches increases simulation time, the accuracy of the numerical solver is expected to be consistent with other CFD numerical solvers and is not expected to be a source of inaccuracy or a limitation on the use of the model for 49 C.F.R. Part 193 applications.

Time discretization

FLACS time steps are specified in terms of the Courant Friedrich Levy (CFL) number. FLACS defines two CFL numbers. CFLC is defined for the speed of the pressure waves (i.e., speed of sound, c) and CFLV is defined for the speed of the fluid particles (i.e., flow velocity, v). The time step is calculated such that the criterion relating to the CFLC and CFLV numbers are both met. Specification of CFL criteria as a function of time is also possible. For dispersion calculations, CFLC=20 and CFLV=2 are recommended. If stability problems ensue, the user guide recommends that the CFL numbers be reduced by a factor of 2-4. Additional guidance on the selection of CFLC and CFLV and its relation to the grid size is provided in the user documentation.

User input/output

FLACS users must specify the following parameters in defining the scenario to be modeled:

- initial conditions;
- boundary conditions (e.g., wind profile based on speed, direction, stability, etc.);

- gaseous leak sources (i.e., jet/diffuse, size/area, location, direction, start time, duration, velocity, relative turbulence intensity, turbulent length scale, temperature, composition);
- vessel leak sources (i.e., pressure, temperature, volume, heat exchange coefficient, wall temperature, composition, phase);
- liquid leak sources (i.e., shape, substrate material, substrate temperature, optional initial mass, release rate, start time, optional fixed inner radius, optional fixed outer radius, location, insolation)
- optional ignition characteristics (i.e., time, position, size);
- optional structures and objects; and
- any optional mitigation (e.g., waterspray, louvre/relief panels, etc.).

FLACS provides guidance on the selection of these parameters in its user manual for several different types of examples. Based on information supplied, FLACS provides results according to the 3D, 2D, or scalar data specified by the user (e.g., velocity vector field, mole fraction contour surfaces, temperature at a specific location, etc.).

FLACS also employs separate models for flashing and jetting (i.e., high pressure releases), and a sub-model for pool spreading that can be used as input. The separate models and sub-models further reduce computational costs, albeit at the cost of some accuracy. However, the cost in accuracy from the use of the separate models and sub-models is minimal, and is not expected to be a source of inaccuracy or a limitation of the model for 49 C.F.R. Part 193 applications.

FLACS can model multiple concurrent gaseous leak sources and vessel leak sources, as well as one liquid leak source at different locations. For applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which references sections 2.2.3.3 and 2.2.3.4 of NFPA 59A (2001 edition). Section 2.2.3.3 and 2.2.3.4 of NFPA 59A (2001 edition) requires the evaluation of a LNG design spill specified in 2.2.3.5, which requires the examination of specific scenarios with a single release; therefore, the evaluation of a single release would be appropriate for 49 C.F.R. § 193.2059 applications.

The input and output parameters should be included with model submissions for use in exclusion zone calculations.

Liquid flashing and jetting

FLACS CFD dispersion model is limited to modeling single-phase (gaseous) flow. Therefore, the FLACS software package contains a separate flash utility model, FLASH, to predict the effects of flashing and jetting from superheated pressurized (two-phase) releases. The FLASH model determines the flash fraction from a liquid jet and the aerosol formation and rainout. The FLASH model also determines the axial distance when all the liquefied gas inside the jet has vaporized along with the vaporized jet diameter, mass flow rate, temperature, and mass and volume fraction of released gas in the entrained vaporized jet (i.e., equivalence ratio). These parameters are used as input into FLACS. The FLASH model assumes the jet axis lies in the horizontal plane, and, therefore the FLASH model may not be suitable for predicting jetting and rainout from non-horizontal releases. For applications pertinent to this study, FLACS will be

used in accordance with 49 C.F.R. § 193.2059, which does not specify a release direction. However, 49 C.F.R. § 193.2059 gives deference to conditions that result in longer predicted downwind dispersion distances; therefore, the conservative assumption that the release is horizontal (i.e., worst case) is appropriate for 49 C.F.R. § 193.2059 applications and not seen as a limitation. The FLASH model determines the rainout fraction based on the initial droplet diameter exceeding a critical value, and is independent of release height. This assumption can under-predict the rainout fraction and result in no rainout. In some circumstances this may be conservative, but in other circumstances it may not be conservative. Therefore it is recommended that if the FLASH utility model is used, that a sensitivity analysis to the liquid rainout fraction is conducted.

In addition, the FLASH model assumes the jet may expand freely in the region of interest, and ignores potential obstacles between the release point and the modeled parameters. These assumptions will most likely be conservative (i.e., producing longer dispersion distances) as less rainout and turbulence will occur without the presence of obstacles. The model contains the properties for eight substances, including all the major components that constitute typical LNG compositions. In addition, the user has the ability to define other materials and properties not included in the contained list, including single-component or multi-component mixtures.

A separate model, JET, can model the initial expansion of a choked flow from gaseous jet sources to ambient pressure. The JET utility model reads the leak conditions (sonic or subsonic pressure) and calculates parameters assuming there is an isentropic flow from the pressurized reservoir (i.e., pipe or container) through the nozzle (i.e., orifice). The flow path passes through a single normal shock where Rankine Hugoniot relations are utilized, followed by expansion into ambient air. No air entrainment is considered. The area and subsonic velocity after shock for the expanded jet is determined by the JET utility model and provided in the output files. The JET utility model has been extended to include non-ideal gas behavior by using an Abel-Noble equation of state (most relevant for hydrogen). Given the temperature and pressure in the pressurized vessel, the temperature, pressure, density and velocity at the release nozzle are calculated.

The grid needs to be refined in the area of a jet source. If the grid is not refined and too low of a grid resolution is applied in a jet source cell, the gas concentration may be artificially reduced when mixed with the air in the CV. For example, if the diameter of the jet source is only half of the grid cell dimension, the maximum concentration immediately downstream of the jet source may be artificially reduced to 25% of the specified jet source concentrations. Similarly, if the diameter of the jet source is only a third of the grid cell dimension, the maximum concentration immediately downstream of the jet source may be artificially reduced to approximately 10% of the specified jet source concentration. For cases where the release is not expected to influence the flow in the grid cell where it is released, a DIFFUSE leak option is available to provide a no-momentum gaseous source release.

Liquid pool spreading

As previously mentioned, FLACS CFD dispersion model is limited to modeling single-phase (gaseous) flow. Therefore, the FLACS software package contains a pool spread sub-model that

predicts the spread of, and evaporation from, a flammable liquid. The pool spread is based on a two-dimension shallow-layer equation modeling approach. The shallow water equations are solved at each time-step using an upstream discretization scheme on the xy-grid and a Runge-Kutta method that is 3rd order accurate in time and 1st order accurate in space. The shallow-layer modeling approach does not neglect viscous forces, and vertical variations, in the flammable liquid, but does neglect surface tension forces. The pool vaporization is defined based on the heat transfer associated with the wind, pool size, substrate material and temperature, and insolation. Alternatively, the user can assume a certain pool size and vaporization rate and define a transient release rate from the pool area with cold gas (e.g., at the boiling point). This allows FLACS to be used for releases that result in the emanation of vapors from regular sources (i.e., circular or rectangular liquid pools), irregular sources (i.e., irregularly spreading liquid pools), or high aspect ratio sources (i.e., trenches, or irregular liquid pools).

Wind profile

FLACS is limited to simulating steady state and periodic wind profiles. The period of the wind direction can be defined by specifying the amplitude and frequency of a sinusoidal wave in the x-, y-, and z- directions. Assuming a steady state or periodic wind speed and direction is often sufficient for hazard analyses, but can pose some limitation in validation against experimental data where varying wind speed and direction cannot be portrayed by sinusoidal functions. However, assuming a steady wind direction will generally produce higher maximum arc-wise gas concentrations, because there would be less cloud meander and turbulent mixing caused from the change in wind direction. Steady state or periodic wind speed and direction are not expected to be a limitation of the model for 49 C.F.R. Part 193 applications. Assuming lower wind speeds will generally result in higher downwind concentrations and assuming a higher wind speed will generally result in lower downwind concentrations. FLACS may also be supplied with zero wind speed conditions. For applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with a wind speed of 4.5 mph (2.01 m/s) at a reference height of 10 meters for models that result in longer predicted downwind dispersion distances at lower wind speeds. The weather conditions reflective of the site should be included with model submissions for use in exclusion zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

Sloped and varying level terrain

Sloped or varying terrain will affect the gravity spreading of a dense gas release. For dense gas releases, such as LNG vapor, the cloud will be stretched out as the dense gas plume flows along downward slopes. Therefore, for downward slopes, the centerline concentrations may be over-predicted in the near field, but under-predicted in the far field. Correspondingly, cross-wise concentrations and cloud widths may be over-predicted in the near field, but under-predicted in the far field. In contrast, upward slopes will oppose the movement of the dense gas, causing the vapor to accumulate and spread perpendicular to the upward slopes. Therefore, for upward slopes, the centerline concentrations may be under-predicted in the near field, but over-predicted in the far field. Correspondingly, cross-wise concentrations and cloud widths may be under-predicted in the near field, but over-predicted in the far field. As previously discussed, FLACS

can account for sloped or varying terrain by a change in gravity vector. However, the structured Cartesian grid may cause inaccuracies if specifying an undulating terrain or a slope relative to the gravity vector. This was shown in previous validation studies of Burro 8, where the terrain was attempted to be modeled on a Cartesian grid, which appeared to prevent the migration of the vapor cloud. Therefore, FLACS may only be appropriate for modeling dispersion along constant sloped surfaces through modification of the gravity vector. Accordingly, there may be cases where FLACS should not be used to model dispersion along downward slopes or varying terrain where the model may under-predict concentrations. In addition, FLACS may not be appropriate for modeling dispersion along undulating terrain or slopes through modification of the geometry, which may be influenced by the Cartesian grid stepping. Site grade information should be included with model submissions for use in exclusion zone calculations.

Varying surface roughness terrain

FLACS is limited to the specification of a single surface roughness. FLACS cannot account for terrain with varying surface roughness length. However, assuming an unobstructed flow field with uniform surface roughness is often sufficient. In addition, FLACS can be specified to explicitly model obstructions within the flow field, which the surface roughness is based upon. Assuming a higher surface roughness (or explicitly including obstructions) will generally result in lower downwind concentrations and assuming a lower surface roughness (or omitting obstructions) will generally result in higher downwind concentrations. FLACS should be specified with the lowest surface roughness that is reflective of the area to produce conservative results. For applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which specifies the surface roughness of 0.03 m or higher. The 0.03 m surface roughness prescribed in 49 C.F.R. § 193.2059 would generally provide 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 ten times the height of the obstacles encountered by the vapor cloud. Lower surface roughness values should be considered for LNG releases that disperse over water. Site location should be included with model submissions for use in exclusion zone calculations.

Atmospheric stability

FLACS is limited to the specification of stable atmospheric stability. FLACS is unable to simulate unstable atmospheric stability classes (i.e., Pasquill-Gifford classes A, B, and C) without producing an error. Lower atmospheric stabilities generally produce lower downwind concentrations and dispersion distances, and higher atmospheric stabilities produce higher downwind concentrations and dispersion distances. For applications pertinent to this decision, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with an atmospheric stability (Pasquill-Gifford Class) of F. The F stability prescribed in 49 C.F.R. § 193.2059 would generally provide conservative results for LNG releases that disperse over land or water. Therefore, this is not seen as a large limitation of the model. However, this limitation would affect the validation results against unstable atmospheric stabilities, which can cause the model to appear more conservative in those cases (i.e., Burro 3, Coyote 3, Coyote 5) than it actually is.

This has been taken into account when considering a safety margin for the model. The weather conditions reflective of the site should be included with model submissions for use in exclusion zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

Obstructed flow

FLACS models turbulence generated in the flow field and can take into account the change in flow field around obstructions. For most instances, downwind concentrations assuming unobstructed terrain will be over-predictive since less turbulence, and subsequent mixing, would be generated in the flow field and no obstructions would restrict the movement of the dispersing vapor. However, there are instances where downwind concentrations could be under-predictive due to wind channeling effects (Melton & Cornwell, 2009¹⁴, Gavelli 2011¹⁵) or reduction of release momentum. FLACS is able to model these wind channeling effects that may occur between adjacent LNG storage tanks, buildings, or large structures. FLACS is also able to model a reduction of the release momentum that may occur when a high momentum release impinges on an obstruction, which may result in less turbulent mixing from the initial release and the model being under-predictive for downwind concentrations. Therefore, obstructions should be included if the release channels between large adjacent structures. In addition, obstructions should be included if the release impinges on an obstruction. The facility layout should be included with model submissions for use in exclusion zone calculations.

As previously discussed, FLACS accounts for atmospheric turbulent mixing and dilution by calculating the generation and dissipation of TKE using a two-equation standard k-epsilon turbulence model. URANS and the k-epsilon turbulence model do not explicitly calculate the stochastic turbulent fluctuations. Therefore, concentrations should be provided with a safety factor of 2 for the LFL to account for estimated peak to mean turbulent fluctuations. FLACS does not contain any other models to account for turbulence. Other models, such as Large Eddy Simulation (LES), are available that may provide better fidelity, since LES will directly calculate stochastic turbulent fluctuations resolved by the grid, but will be at a much higher computation cost. For gaseous jet leaks, FLACS models the turbulence associated with the jet release. For gaseous diffuse leaks and liquid leaks, turbulence associated with the release would be negligible. Assuming no turbulence at a low-momentum source (i.e., turbulence generated at the surface of a boiling pool) will generally result in higher downwind concentrations because there is less turbulent mixing.

Verification

¹⁴ Melton, T.A., Cornwell, J.B. (2009). *LNG Trench Dispersion Modeling Using Computational Fluid Dynamics*. 12th Annual Symposium, Mary Kay O'Connor Process Safety Center.

¹⁵ Gavelli, F., Davis, S.G., Hansen, O.H., (2011), *User Beware: When Simple Consequence Models Can Give the Wrong Answers*, *Proceedings of AIChE Spring Meeting, 7th Global Congress on Process Safety, Chicago, IL, March 16, 2011*.

GexCon has verified FLACS numerical results against a number of “simple” analytical solutions. For more “complex” scenarios where analytical solutions do not exist, GexCon has carried out tests to check symmetry and directional similar behavior of numerical schemes.

In addition, GexCon has a quality management system that helps assure the models have been translated into the program code correctly. GexCon states that it follows many of the generally accepted quality assurance publications, certifications, and standards, as well as quality management systems which require a number of software development and maintenance specific items. GexCon is not yet ISO 9001 certified, and it is not clear as to whether their software division adheres to all of the requirements in ISO 90003 or TickIT. Quality assurance measures are in place, such as using version control systems when writing source code. Identical simulations are performed to compare results on various software and computer platforms (i.e., Linux and Windows). Similar tests are also provided for different compiler optimizations to discover optimization errors. GexCon’s quality assurance program does contain a software “bug” tracking log reported by users of the software, which addresses some of the requirements in ISO 90003 and TickIT. Although not fully certified to ISO 90001, GexCon appears to have an acceptable quality management system in place to assure FLACS is properly implemented and any bugs are resolved in a timely fashion. The software is proprietary, which ensures better quality control, and its executable files are available at a cost to the public.

Validation

The FLACS model is able to simulate dispersion over unobstructed and obstructed flow fields, including sloped terrain. Therefore, the current validation study includes all of the following trials specified in the Model Evaluation Protocol:

- LNG Field Trials: Maplin Sands 27, 34, 35; Burro 3, 7, 8, 9; Coyote 3, 5, 6; Falcon 1, 3, 4;
- Other Field Trials: Thorney Island 45, 47; and
- Wind Tunnel Experiments: CHRC A, B, C; BA-Hamburg DA0120 (Unobstructed), DAT223 (Unobstructed 2); 039051 (Upwind Fence), 039072 (Upwind Fence 2), DA0501 (Downwind Fence), DA0532 (Downwind Fence 2), 039094/039095 (Circular Fence), 039097 (Circular Fence 2), DAT647 (Slope 1), DAT631 (Slope 2), DAT632 (Slope 3), DAT637 (Slope 4); and BA-TNO TUV01, TUV02, FLS.

The CHRC tests were validated at wind-tunnel scale; however the BA Hamburg and BA TNO tests were validated at field scale to satisfy the FLACS User Guide grid size guidelines. Specifically, the grid cell size should be approximately 1 centimeter or greater.

As shown in Table 1, FLACS meets the MEP quantitative acceptance criteria for maximum arc-wise gas concentration for unobstructed and obstructed scaled wind tunnel tests, which are all based on long time averages. FLACS also meets the MEP quantitative acceptance criteria for maximum arc-wise gas concentration for unobstructed field trials with short time averages and for unobstructed trials with long time averages with the exception of the geometric variance (VG). The unobstructed trials with long time averages includes both the field trials with long

time averages and the unscaled wind tunnel tests, which are all based on long time averages. However, FLACS does not meet the MEP quantitative acceptance criteria for maximum arc-wise gas concentration for obstructed field trials with short time averages or for unobstructed trials with long time averages. The unobstructed trials with long time averages includes both the field trials with long time averages (i.e., Falcon tests) and the unscaled obstructed wind tunnel tests, which are all based on long time averages. FLACS generally performs better for maximum gas concentration arc-wise distances, but shows similar trends to the prediction of maximum arc-wise gas concentrations,

FLACS does not meet most of the MEP quantitative acceptance criteria for prediction of maximum point-wise gas concentrations. FLACS shows a wide degree of scatter for prediction of point-wise gas concentrations for all groups, but with better agreement for wind tunnel tests where conditions are more easily controlled and not influenced by gusts of wind or other phenomena not readily captured by experimental data or replicated in simulations. FLACS generally performs better for maximum cloud width predictions, but shows similar trends to the prediction of maximum point-wise gas concentrations,

As shown in Table 1, and supported by the statistical performance measure values, FLACS is generally over-predictive of maximum arc-wise concentrations for unobstructed short time and long time averages, is generally in good agreement of maximum arc-wise concentrations for unobstructed and obstructed scaled wind tunnel tests, and is generally under-predictive of maximum arc-wise concentrations for obstructed trials with short time averages and obstructed trials with long time averages. A large majority of FLACS maximum arc-wise concentration predictions are within a factor of 2 with the exception of obstructed short time averages (i.e., Falcon tests).

**Table 1:
SPM Evaluation against Quantitative Assessment Criteria: MEP**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Arc-wise Gas Concentration									
Unobstructed Field Trials (Short Time Avg.)	0.02	1.29	0.45	17.52	82%	1.29	1.29	N/A	N/A
Unobstructed Trials (Long Time Avg.)	-0.09	1.19	0.65	50.38	57%	1.57	N/A	N/A	N/A
Obstructed Field Trials (Short Time Avg.)	0.96	2.97	0.99	3.77	11%	0.36	0.43	N/A	N/A
Obstructed Trials (Long Time Avg.)	0.55	1.78	0.37	1.51	73%	0.58	N/A	N/A	N/A
Unobstructed Wind-Tunnel Tests (Scaled)	0.27	1.33	0.23	1.29	82%	0.82	N/A	N/A	N/A
Obstructed Wind-Tunnel Tests (Scaled)	0.16	1.18	0.18	1.22	88%	0.91	N/A	N/A	N/A
Maximum Gas Concentration Arc-wise Distance									
Unobstructed Field Trials (Short Time Avg.)	-0.36	0.69	0.19	1.23	92%	N/A	N/A	1.50	1.12
Unobstructed Trials (Long Time Avg.)	-0.32	0.71	0.32	1.46	73%	N/A	N/A	1.60	N/A
Obstructed Field Trials (Short Time Avg.)	1.47	9.66	2.34	>100	11%	N/A	N/A	0.18	0.30
Obstructed Trials (Long Time Avg.)	0.39	1.55	0.30	1.60	91%	N/A	N/A	0.71	N/A
Unobstructed Wind-Tunnel Tests (Scaled)	0.21	1.23	0.12	1.14	100%	N/A	N/A	0.85	N/A
Obstructed Wind-Tunnel Tests (Scaled)	0.00	1.00	0.10	1.11	97%	N/A	N/A	1.06	N/A

However, the MEP specific performance measures and quantitative acceptance criteria are based on an average of trials, which can be misleading. Therefore, it was recognized in the Advisory Bulletin that the approval or disapproval of a model should not be contingent only on the average of the experiments meeting the MEP quantitative acceptance criteria. Careful examination of all the sensor data and trends must be considered in concert with the MEP quantitative acceptance criteria. As shown in Figure 1 and Table 2, these trends provide additional insight into the model performance against subsets of data.

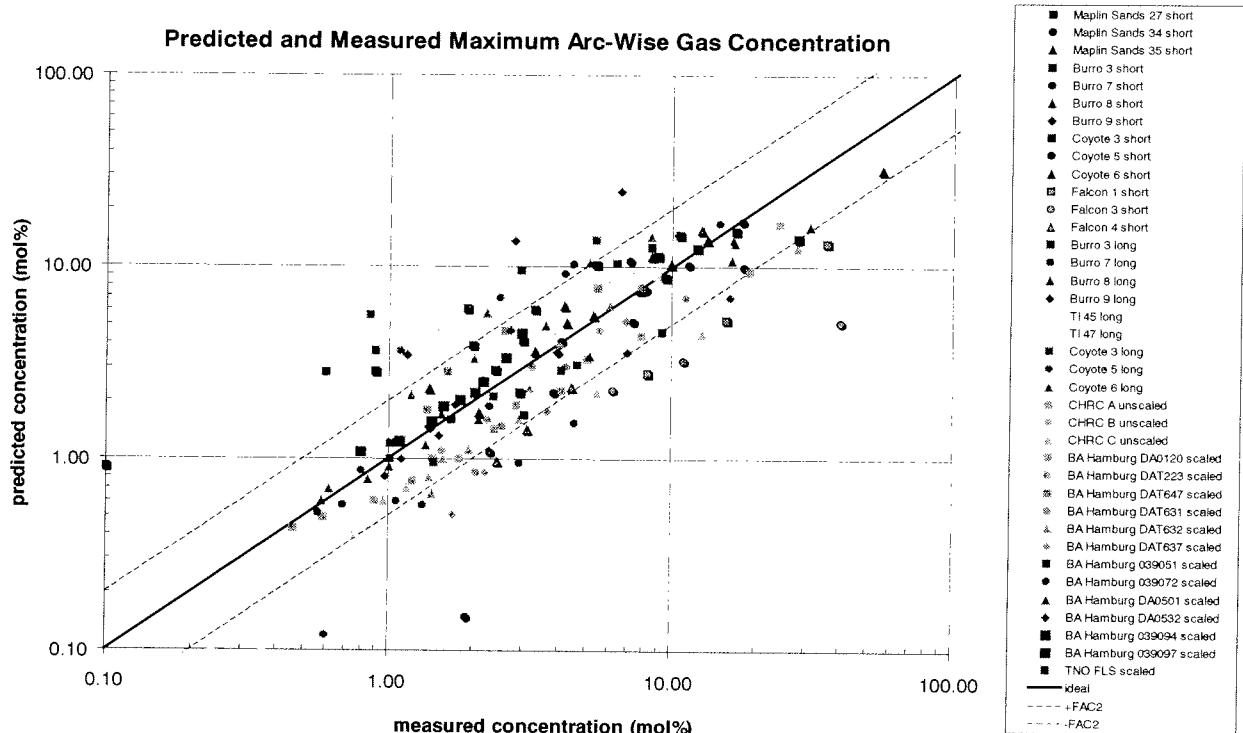


Figure 1 Predicted Concentration against Measured Concentration

**Table 2:
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	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)	-0.28	0.70	0.39	1.97	88%	2.12	1.40	N/A	N/A
Maplin Sands 34 (short)	0.46	1.60	0.23	1.27	100%	0.63	0.80	N/A	N/A
Maplin Sands 35 (short)	-0.08	0.92	0.02	1.02	100%	1.09	1.08	N/A	N/A
Burro 3 (short)	0.35	7.09	1.39	>1000	25%	1.23	1.59	N/A	N/A
Burro 3 (long)	-0.04	3.94	1.51	>1000	50%	1.95	N/A	N/A	N/A
Burro 7 (short)	0.06	1.06	0.16	1.18	100%	1.02	0.86	N/A	N/A
Burro 7 (long)	-0.24	0.78	0.23	1.28	67%	1.42	N/A	N/A	N/A
Burro 8 (short)	0.19	1.21	0.10	1.11	100%	0.86	1.15	N/A	N/A
Burro 8 (long)	0.25	1.29	0.18	1.21	100%	0.83	N/A	N/A	N/A
Burro 9 (short)	-0.09	0.91	0.04	1.04	100%	1.12	1.01	N/A	N/A
Burro 9 (long)	-1.16	0.26	1.35	6.11	0%	3.86	N/A	N/A	N/A
Coyote 3 (short)	-0.12	1.96	1.19	>1000	60%	2.09	1.96	N/A	N/A
Coyote 3 (long)	-0.52	2.50	1.90	>1000	0%	4.09	N/A	N/A	N/A
Coyote 5 (short)	0.52	2.01	0.69	4.08	60%	0.67	0.98	N/A	N/A
Coyote 5 (long)	-0.30	0.75	0.88	3.12	20%	2.34	N/A	N/A	N/A
Coyote 6 (short)	-0.30	0.74	0.11	1.12	100%	1.29	1.46	N/A	N/A
Coyote 6 (long)	-0.63	0.52	0.42	1.59	60%	2.01	N/A	N/A	N/A
Thorney Island 45 (long)	0.40	1.53	0.36	1.53	78%	0.73	N/A	N/A	N/A
Thorney Island 47 (long)	-0.31	0.70	0.59	2.11	50%	1.90	N/A	N/A	N/A
Falcon 1 (short)	0.97	2.88	0.94	3.06	0%	0.35	0.94	N/A	N/A
Falcon 1 (long)	0.75	2.24	0.62	2.05	33%	0.46	N/A	N/A	N/A
Falcon 3 (short)	1.19	4.18	1.48	9.48	0%	0.26	0.40	N/A	N/A
Falcon 3 (long)	0.68	2.06	0.53	1.86	67%	0.51	N/A	N/A	N/A
Falcon 4 (short)	0.74	2.17	0.55	1.85	33%	0.46	0.56	N/A	N/A
Falcon 4 (long)	0.38	1.47	0.15	1.17	100%	0.68	N/A	N/A	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Arc-Wise Gas Concentration (cont'd)									
CHRC A (un-scaled)	0.44	1.57	0.21	1.25	80%	0.64	N/A	N/A	N/A
CHRC B (un-scaled)	0.32	1.38	0.12	1.14	100%	0.73	N/A	N/A	N/A
CHRC C (un-scaled)	0.64	1.95	0.44	1.63	63%	0.52	N/A	N/A	N/A
Hamburg DA0120 (scaled)	0.42	1.53	0.21	1.24	100%	0.67	N/A	N/A	N/A
Hamburg DAT223 (scaled)	0.05	1.06	0.01	1.01	100%	0.95	N/A	N/A	N/A
Hamburg 039051 (scaled)	0.46	1.60	0.22	1.26	100%	0.63	N/A	N/A	N/A
Hamburg 039072 (scaled)	0.61	1.92	0.50	1.81	50%	0.57	N/A	N/A	N/A
Hamburg DA0501 (scaled)	0.07	1.07	0.03	1.03	100%	0.94	N/A	N/A	N/A
Hamburg DA0532 (scaled)	0.18	1.20	0.20	1.24	86%	0.91	N/A	N/A	N/A
Hamburg 039094 (scaled)	-0.17	0.84	0.04	1.04	100%	1.20	N/A	N/A	N/A
Hamburg 039097 (scaled)	-0.21	0.81	0.06	1.06	100%	1.24	N/A	N/A	N/A
Hamburg DAT647 (scaled)	-0.43	0.65	0.20	1.23	100%	1.56	N/A	N/A	N/A
Hamburg DAT631 (scaled)	0.42	1.55	0.27	1.34	75%	0.68	N/A	N/A	N/A
Hamburg DAT632 (scaled)	0.38	1.48	0.23	1.28	75%	0.71	N/A	N/A	N/A
Hamburg DAT637 (scaled)	0.73	2.20	0.63	2.09	25%	0.48	N/A	N/A	N/A
TNO FLS (scaled)	0.17	1.19	0.10	1.12	83%	0.87	N/A	N/A	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Gas Concentration Arc-Wise Distance									
Maplin Sands 27 (short)	-0.36	0.69	0.19	1.22	86%	N/A	N/A	1.49	1.33
Maplin Sands 34 (short)	0.06	1.06	0.00	1.00	100%	N/A	N/A	0.94	0.78
Maplin Sands 35 (short)	-0.34	0.70	0.14	1.16	100%	N/A	N/A	1.50	1.10
Burro 3 (short)	-0.69	0.49	0.48	1.70	33%	N/A	N/A	2.07	1.42
Burro 3 (long)	-0.99	0.33	1.05	3.98	0%	N/A	N/A	3.26	N/A
Burro 7 (short)	-0.43	0.63	0.38	1.53	58%	N/A	N/A	1.75	0.91
Burro 7 (long)	-0.64	0.50	0.55	1.90	33%	N/A	N/A	2.15	N/A
Burro 8 (short)	-0.31	0.73	0.11	1.12	100%	N/A	N/A	1.38	1.16
Burro 8 (long)	-0.65	0.50	0.53	1.91	67%	N/A	N/A	2.18	N/A
Burro 9 (short)	-0.31	0.73	0.16	1.18	88%	N/A	N/A	1.42	1.00
Burro 9 (long)	-0.62	0.52	0.45	1.67	50%	N/A	N/A	2.01	N/A
Coyote 3 (short)	-0.63	0.52	0.40	1.53	100%	N/A	N/A	1.92	1.67
Coyote 3 (long)	-0.94	0.36	0.89	2.86	0%	N/A	N/A	2.79	N/A
Coyote 5 (short)	-0.22	0.80	0.04	1.05	100%	N/A	N/A	1.25	0.98
Coyote 5 (long)	-0.84	0.41	0.71	2.23	0%	N/A	N/A	2.45	N/A
Coyote 6 (short)	-0.38	0.68	0.13	1.18	100%	N/A	N/A	1.49	1.29
Coyote 6 (long)	-0.61	0.53	0.31	1.52	75%	N/A	N/A	1.90	N/A
Thorney Island 45 (long)	0.09	1.10	0.07	1.08	100%	N/A	N/A	0.94	N/A
Thorney Island 47 (long)	-0.30	0.74	0.15	1.17	100%	N/A	N/A	1.40	N/A
Falcon 1 (short)	1.15	6.40	1.67	>100	33%	N/A	N/A	0.31	0.42
Falcon 1 (long)	-0.04	0.96	0.04	1.04	100%	N/A	N/A	1.06	N/A
Falcon 3 (short)	1.75	19.5	3.08	>1000	13%	N/A	N/A	0.31	0.42
Falcon 3 (long)	1.03	4.23	1.51	25.9	50%	N/A	N/A	0.39	N/A
Falcon 4 (short)	1.50	7.21	2.26	53.7	0%	N/A	N/A	0.14	0.29
Falcon 4 (long)	0.55	1.76	0.31	1.38	100%	N/A	N/A	0.57	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Gas Concentration Arc-Wise Distance (cont'd)									
CHRC A (un-scaled)	0.27	1.32	0.09	1.10	100%	N/A	N/A	0.76	N/A
CHRC B (un-scaled)	0.09	1.10	0.02	1.02	100%	N/A	N/A	0.92	N/A
CHRC C (un-scaled)	0.46	1.61	0.26	1.32	88%	N/A	N/A	0.64	N/A
Hamburg DA0120 (scaled)	0.39	1.49	0.18	1.21	100%	N/A	N/A	0.68	N/A
Hamburg DAT223 (scaled)	0.01	1.01	0.01	1.01	100%	N/A	N/A	1.00	N/A
Hamburg 039051 (scaled)	0.31	1.37	0.10	1.11	100%	N/A	N/A	0.73	N/A
Hamburg 039072 (scaled)	0.30	1.36	0.12	1.13	100%	N/A	N/A	0.75	N/A
Hamburg DA0501 (scaled)	-0.02	0.98	0.02	1.02	100%	N/A	N/A	1.03	N/A
Hamburg DA0532 (scaled)	0.03	1.03	0.16	1.18	86%	N/A	N/A	1.07	N/A
Hamburg 039094 (scaled)	-0.25	0.78	0.07	1.07	100%	N/A	N/A	1.29	N/A
Hamburg 039097 (scaled)	-0.37	0.68	0.15	1.17	100%	N/A	N/A	1.47	N/A
Hamburg DAT647 (scaled)	-0.26	0.77	0.09	1.10	100%	N/A	N/A	1.32	N/A
Hamburg DAT631 (scaled)	0.25	1.28	0.08	1.09	100%	N/A	N/A	0.79	N/A
Hamburg DAT632 (scaled)	0.21	1.24	0.07	1.07	100%	N/A	N/A	0.82	N/A
Hamburg DAT637 (scaled)	0.45	1.59	0.23	1.27	100%	N/A	N/A	0.64	N/A
TNO FLS (scaled)	0.18	1.20	0.11	1.13	100%	N/A	N/A	0.87	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	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)	1.84	>1000	3.61	>1000	10%	0.07	N/A	N/A	N/A
Burro 3 (long)	1.76	>1000	3.61	>1000	10%	0.15	N/A	N/A	N/A
Burro 7 (short)	1.11	28.4	2.17	>1000	40%	0.46	N/A	N/A	N/A
Burro 7 (long)	0.88	21.5	2.24	>1000	10%	0.81	N/A	N/A	N/A
Burro 8 (short)	0.05	1.25	0.53	5.90	71%	1.18	N/A	N/A	N/A
Burro 8 (long)	0.06	1.28	0.55	7.91	67%	1.20	N/A	N/A	N/A
Burro 9 (short)	1.32	>1000	2.86	>1000	20%	0.42	N/A	N/A	N/A
Burro 9 (long)	1.13	>1000	3.11	>1000	10%	1.14	N/A	N/A	N/A
Coyote 3 (short)	1.38	>1000	3.01	>1000	8%	0.53	N/A	N/A	N/A
Coyote 3 (long)	1.25	>1000	3.31	>1000	0%	2.10	N/A	N/A	N/A
Coyote 5 (short)	1.42	>1000	2.65	>1000	21%	0.25	N/A	N/A	N/A
Coyote 5 (long)	1.08	>100	2.73	>1000	7%	0.83	N/A	N/A	N/A
Coyote 6 (short)	0.21	13.7	1.74	>1000	31%	1.80	N/A	N/A	N/A
Coyote 6 (long)	0.27	10.9	1.64	>1000	31%	1.51	N/A	N/A	N/A
Thorney Island 45 (long)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Thorney Island 47 (long)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Falcon 1 (short)	1.18	>100	1.64	>1000	0%	0.28	N/A	N/A	N/A
Falcon 1 (long)	1.10	>100	1.61	>1000	19%	0.35	N/A	N/A	N/A
Falcon 3 (short)	1.51	57.3	2.52	>1000	5%	0.16	N/A	N/A	N/A
Falcon 3 (long)	1.36	44.6	2.26	>1000	21%	0.24	N/A	N/A	N/A
Falcon 4 (short)	1.29	>100	2.56	>1000	20%	0.52	N/A	N/A	N/A
Falcon 4 (long)	1.43	>1000	2.69	>1000	23%	0.26	N/A	N/A	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Point-Wise Gas Concentration (cont'd)									
CHRC A (un-scaled)	0.46	2.15	0.70	23.1	71%	0.97	N/A	N/A	N/A
CHRC B (un-scaled)	0.05	1.14	0.38	2.39	80%	1.12	N/A	N/A	N/A
CHRC C (un-scaled)	0.59	2.22	0.67	6.67	60%	0.63	N/A	N/A	N/A
Hamburg DAT223 (scaled)	0.54	2.59	0.67	36.9	63%	0.65	N/A	N/A	N/A
Hamburg DAT647 (scaled)	-0.66	0.50	0.51	1.80	50%	2.12	N/A	N/A	N/A
Hamburg DAT631 (scaled)	0.06	1.06	0.29	1.39	75%	1.14	N/A	N/A	N/A
Hamburg DAT632 (scaled)	0.02	1.02	0.26	1.33	75%	1.14	N/A	N/A	N/A
Hamburg DAT637 (scaled)	0.54	1.85	0.63	2.36	50%	0.67	N/A	N/A	N/A
TNO TUV01 (scaled)	0.23	44.9	0.62	>1000	75%	0.95	N/A	N/A	N/A
TNO TUV02 (scaled)	0.48	46.2	0.95	>1000	56%	0.84	N/A	N/A	N/A
TNO FLS (scaled)	0.61	12.6	1.08	>1000	59%	0.69	N/A	N/A	N/A

**Table 2 (cont'd):
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data**

Data Set	Quantitative Criteria								
	-0.4<MRB <0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Cloud Width									
Burro 3 (short)	0.69	2.05	0.48	1.68	0%	N/A	N/A	0.49	N/A
Burro 3 (long)	0.65	1.96	0.43	1.58	50%	N/A	N/A	0.51	N/A
Burro 7 (short)	0.74	2.25	0.66	2.24	33%	N/A	N/A	0.48	N/A
Burro 7 (long)	0.83	2.57	0.84	3.24	67%	N/A	N/A	0.44	N/A
Burro 8 (short)	-0.03	0.97	0.03	1.04	100%	N/A	N/A	1.04	N/A
Burro 8 (long)	0.00	1.00	0.02	1.02	100%	N/A	N/A	1.01	N/A
Burro 9 (short)	1.16	4.12	1.49	10.0	33%	N/A	N/A	0.28	N/A
Burro 9 (long)	0.98	3.15	1.10	5.17	33%	N/A	N/A	0.36	N/A
Coyote 3 (short)	0.97	5.12	1.40	>100	67%	N/A	N/A	0.41	N/A
Coyote 3 (long)	1.05	5.64	1.49	>100	33%	N/A	N/A	0.36	N/A
Coyote 5 (short)	1.36	15.9	2.19	>1000	20%	N/A	N/A	0.23	N/A
Coyote 5 (long)	1.36	16.1	2.21	>1000	40%	N/A	N/A	0.23	N/A
Coyote 6 (short)	0.18	1.20	0.08	1.09	100%	N/A	N/A	0.85	N/A
Coyote 6 (long)	0.17	1.19	0.06	1.07	100%	N/A	N/A	0.86	N/A
Falcon 1 (short)	0.31	1.37	0.12	1.13	100%	N/A	N/A	0.74	N/A
Falcon 1 (long)	0.41	1.52	0.19	1.22	100%	N/A	N/A	0.66	N/A
Falcon 3 (short)	0.64	1.96	0.43	1.60	33%	N/A	N/A	0.52	N/A
Falcon 3 (long)	0.72	2.13	0.53	1.79	33%	N/A	N/A	0.47	N/A
Falcon 4 (short)	0.78	2.28	0.61	1.98	0%	N/A	N/A	0.44	N/A
Falcon 4 (long)	0.80	2.33	0.64	2.05	0%	N/A	N/A	0.43	N/A
CHRC A (un-scaled)	0.05	1.05	0.00	1.00	100%	N/A	N/A	0.95	N/A
CHRC B (un-scaled)	0.11	1.12	0.02	1.02	100%	N/A	N/A	0.90	N/A
CHRC C (un-scaled)	0.02	1.02	0.00	1.00	100%	N/A	N/A	0.98	N/A
TNO FLS (scaled)	0.17	1.18	0.04	1.04	100%	N/A	N/A	0.85	N/A

FLACS is generally in good agreement with maximum arc-wise concentrations for unobstructed field trials. Nearly all of the data are within a factor of 2, often within the experimental uncertainty bounds. FLACS generally under-predicts arc-wise gas concentrations for unobstructed field trials with short time averages and over-predicts arc-wise gas concentrations for unobstructed field trials with long time averages with the exception of Burro 8. FLACS does not illustrate a general bias (i.e., under-predictive or over-predictive) for particular datasets, such as a bias for dispersion over land compared to dispersion over water. In addition, FLACS does not show any definitive trends as the vapor cloud disperses downwind. However, FLACS predicted near zero concentrations in the far field for Burro 3 and Coyote 3, which resulted in a significant under-prediction and caused FLACS to not meet the statistical performance measures for maximum arc-wise concentrations for unobstructed field trials. However, these trials, and to a lesser extent Coyote 5, were the only trials that showed this trend and were the only trials where the measured atmospheric stabilities could not be simulated by FLACS due to numerical errors.

FLACS may be slightly more under-predictive for low wind speeds (<2 m/s) and high atmospheric stabilities (F stability), which is especially pertinent to the federal regulations under 49 C.F.R. Part 193. However, predictions are within a factor of 2 and are consistent with other predictions at higher wind speeds.

FLACS also is generally in good agreement with maximum arc-wise concentrations for unobstructed wind tunnel experiments. Nearly all predictions are within a factor of 2. FLACS does not illustrate any bias for any particular datasets, but showed a trend for unobstructed sloped trials with increasing downward slope. At a 4% slope, FLACS over-predicted concentrations in the near field and far field. At an 8.6% slope, FLACS predicted concentrations approximately equal in the near field and under-predicted concentrations in the far field by a factor of 2. At an 11.6% slope, FLACS under-predicted concentrations in the near field by a factor of 2 or less, and under-predicted concentrations in the far field by a factor of 2 or more.

FLACS is generally under-predictive by a factor of 2 or more for maximum arc-wise concentrations for obstructed trials with short time averages (i.e., Falcon trials). However, the Falcon trials had multiple release locations that showed significant amounts of flashing and source turbulence, which may have also affected the results. The under-prediction may also be partly attributed to the sensor placement within the simulation not coinciding with the maximum concentration. GexCon conducted a sensitivity test for Maplin Sands on sensor placement and illustrated a high degree of sensitivity to sensor placement relative to the vapor cloud due to its narrow profile.

FLACS shows significantly better agreement (but was still generally under-predictive) with maximum arc-wise concentrations for obstructed wind tunnel experiments with most data being within a factor of 2 or less. FLACS was under-predictive for downwind and upwind fences, but compared better with fences downwind where there was less bifurcation of the cloud. FLACS was over-predictive for circular fences where no bifurcation occurred.

FLACS is generally in good agreement or conservative for maximum gas concentration distances with the exception of obstructed field trials (i.e., Falcon trials). FLACS generally compares

better with maximum gas concentration distances, and follows similar trends as the maximum arc-wise concentrations. Nearly all of the data is within a factor of 2 with the exception of obstructed field trials (i.e., Falcon trials). The better agreement is partly because large concentration differences may manifest themselves as much smaller differences in distance and because the maximum distance was not based on a particular sensor location and therefore not subject to the same spatial uncertainties as was the maximum arc-wise concentration.

FLACS shows a wide degree of scatter for prediction of point-wise gas concentrations for unobstructed and obstructed trials with short and long time averages. FLACS predicts more accurately and conservatively for point-wise concentrations that are located at an angle corresponding to the wind direction where the maximum arc-wise concentration often occurred (i.e., “centerline”). FLACS often predicts near-zero concentrations for point-wise gas concentrations for field trials that are located farther from the “centerline”. FLACS shows similar trends for wind tunnel tests, but agrees much better with the data with a majority of the predictions within a factor of 2. The better agreement with wind tunnel tests may be partly because the conditions of wind tunnel tests are more easily controlled (e.g., no cloud meander) and replicated in simulations compared to the conditions of field trials, which are not as readily controlled or captured by experimental measurements or replicated in simulations. In addition, there are a much larger number of sensors in the wind tunnel tests within the cross-stream direction of the cloud.

FLACS compares better with cloud widths compared to maximum point-wise gas concentrations, but still generally under-predicts cloud widths for unobstructed field trials with short and long time averages by a factor of 2 to 4 with the exception of Burro 8. FLACS agrees much better with wind tunnel tests with all the predictions within much less than a factor of 2. The better agreement with cloud widths compared to point-wise gas concentrations is due to the lesser influence by large concentration differences away from the “centerline.” Cloud widths are not a particular concern with 49 C.F.R. Part 193, but may be more important for risk analyses or performance based design of gas detectors.

The maximum arc-wise concentrations for field trials over land are most applicable to the scenarios to be considered under the 49 C.F.R. Part 193 regulations. Although FLACS generally showed good agreement, there are uncertainties that indicate potential under-prediction by a factor of 2. Until these uncertainties are resolved, it is recommended that a safety factor of 2 be used when evaluating predicted maximum arc-wise concentrations from FLACS for unobstructed cases, and a factor of 2 be used when evaluating predicted maximum arc-wise concentrations from FLACS for obstructed cases.

Sensitivity Analyses

All the LNG field trial releases were conducted over water and the associated source terms will be different than those used on land. For spills over water with significant depth, the heat transfer to the pool is generally considered constant due to convective motion of the water. For spills over land, the heat transfer to the pool is generally considered to be transient due to conductive cooling of the substrate. Pressurized releases may further deviate from the more idealized source term for spills over water. However, 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 193.¹⁶ Therefore, for spills over land and pressurized releases, PHMSA recommends that the source term is evaluated before usage. The input and output parameters should be included with model submissions for use in exclusion zone calculations.

FLACS automatically determines the time step based on the CFLC and CFLV criteria specified, and the value is typically on the order of $1/10^{\text{th}}$ of a second or less. Subsequent time-averaging can then be taken from the data output. As with experimental data, longer time averages in FLACS predictions will result in lesser 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. This is demonstrated best in Burro 3 and Coyote 3, and to a lesser extent Coyote 5, where higher atmospheric stabilities were simulated instead of lower atmospheric stabilities due to model limitations. FLACS tends to compare more conservatively with longer time averages. However, short time averages are more appropriate for flammable hazards and should be used when predicting flammable vapor centerline concentrations.

The grid dependence of CFD codes can often be extrapolated based on the order of the numerical solver and grid refinement studies. However, FLACS grid dependence is further complicated by its Cartesian grid and PDR methodology, which affect the resolution of the solid boundaries and the porosity calculations. Reviews of FLACS version 9.0 for the Health and Safety Executive indicated a grid dependency study of unobstructed dense gas releases involving two grids (4m x 4m x 0.5m and 2m x 2m x 0.25m) result in gas concentrations 1.5 to 2 times higher on the finer grid. The present FLACS evaluation (Version 9.1 Release 2) uses base grids for the field trials that are similar to that of the coarse grid in the prior study. Grid refinement around the liquid pool is similar to that recommended in the FLACS User Guide (i.e., 1 meter or finer in the x- and y-direction and finer in the z-direction for dense gases). To analyze the effect of grid specification on the current FLACS evaluation, GexCon conducted a sensitivity analysis for the unobstructed Coyote 3 and obstructed BA Hamburg DA0501 for the vertical grid spacing and streamwise grid spacing away from the source. The results suggest that the vertical grid size selected near the source (typically 1m x 1m x 0.5m) and streamwise grid away from the source (typically 4m x 4m x 0.5m) was sufficient for field scale trials to reach a grid independent solution. However, the streamwise grid size selection near the source was not tested. In addition, the grid size and subsequent grid independence would be case specific, especially if obstacles are included where the Cartesian grid and PDR methodology would have an influence. Although guidelines are provided in the FLACS User Guide to minimize grid-dependence, demonstration of a grid independent or convergent solution better ensures that potential user-error or differences among the approaches taken by various users/stakeholders are reduced. Therefore, PHMSA recommends that a grid sensitivity analysis accompanies 49 C.F.R. § 193.2059 submittals to ensure a grid independent or convergent solution. This is consistent with the FLACS User Guide, which recommends grid sensitivity tests, and is consistent with other technical submittals to other entities, such as the *ASME Journal of Fluids Engineering*.

¹⁶ *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).

GexCon used sinusoidal wind speed functions to more closely match the wind speed of the actual tests of the Burro trials, while the other trials used the average wind speed and direction specified in the MEP. GexCon conducted a sensitivity test of Maplin Sands 35 and Burro trials, which indicated lower wind speeds generally produce higher downwind concentrations and dispersion distances, and higher wind speeds produced lower downwind concentrations and dispersion distances. For applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with a wind speed of 4.5 mph (2.01 m/s) at reference height of 10 meters for models that result in longer predicted downwind dispersion distances at lower wind speeds. The weather conditions reflective of the site should be included with model submissions for use in exclusion zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

The surface roughness values have the largest uncertainties. The values specified in the MEP 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 actually is. Less conservative parameters cause the model to under-predict concentrations by a greater margin, but still is within the quantitative acceptance criteria. For applications pertinent to this study, UDM will be used in accordance with 49 C.F.R. § 193.2059, which specifies the surface roughness of 0.03 m or higher. The 0.03 m surface roughness prescribed in 49 C.F.R. § 193.2059 would generally provide 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 ten times the height of the obstacles encountered by the vapor cloud. Lower surface roughness values should be considered for LNG releases that disperse over water. Site location should be included with model submissions for use in exclusion zone calculations.

GexCon conducted an atmospheric stability sensitivity test of the Burro and Coyote trials, which indicate lower atmospheric stabilities generally produced lower downwind concentrations and dispersion distances, and higher atmospheric stabilities produced higher downwind concentrations and dispersion distances. As previously discussed, FLACS is limited to the specification of stable atmospheric stability. This is not seen as a large limitation of the model when predicting hazard distances, since lower atmospheric stabilities generally produce lower downwind concentrations and dispersion distances, and higher atmospheric stabilities produced higher downwind concentrations and dispersion distances. For applications pertinent to this study, FLACS will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with an atmospheric stability (Pasquill–Gifford Class) of F. The F stability prescribed in 49 C.F.R. § 193.2059 would generally provide conservative results for LNG releases that disperse over land or water. Therefore, this is not seen as a large limitation of the model. However, this limitation would affect the validation results against unstable atmospheric stabilities, which can cause the model to appear more conservative in those cases (i.e., Burro 3, Coyote 3, Coyote 5) than it actually is. This has been taken into account when considering a safety margin for the model. The weather conditions reflective of the site should be included with model submissions for use in exclusion

zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

Ambient temperature and surface temperature had little fluctuation, and, therefore, GexCon did not run any related sensitivity cases. However, higher ambient temperatures and surface temperatures should generally produce lower gas concentrations and downwind dispersion distances. For applications pertinent to this study, UDM will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with an atmospheric temperature equal to the average in the region. The weather conditions reflective of the site should be included with model submissions for use in exclusion zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

The FLACS pool model is limited to ambient pressures of 90 kPa or above. None of the trials had ambient pressures that differed by more than 10% from atmospheric pressure. In order to gauge the sensitivity, the Falcon trials, which had low ambient pressures, were tested. Higher ambient pressure showed higher concentrations and downwind dispersion distances, but did not greatly affect the concentration or resultant statistical performance measures. PHMSA recommends that atmospheric pressure be specified.

Many of the trials did not have ambient relative humidity that differed by more than 10%, but some of the values disagreed with those reported in the original data series reports. Lower ambient relative humidity generally produced higher gas concentrations in the near field, and lower concentrations in the far field, but did not greatly affect the predicted distance to the LFL or the statistical performance measures. For applications pertinent to this study, UDM will be used in accordance with 49 C.F.R. § 193.2059, which specifies the use of weather conditions that occur 90% of time for the area that result in longer predicted downwind dispersion distances than other weather conditions, or alternative conditions with a relative humidity of 50%. The weather conditions reflective of the site should be included with model submissions for use in exclusion zone calculations. If alternative weather conditions are specified, the dispersion distances should be verified to produce the worst case results.

The composition specified in the MEP reflects the composition of the LNG and does not take into account preferential boiloff. The lower molecular weight of methane generally results in higher concentrations and longer dispersion distances. The molecular weight of methane is recommended to be used to account for potential preferential boiloff and conservatism.

Overall, the sensitivity analysis showed concentrations generally differ by less than a factor of 2 from the base case and downwind dispersion distances to the LFL differ by less than a factor of 2.

Model Suitability and Limitations

FLACS has separate utility source term models that can calculate flashing, jetting, and rainout, and a built-in sub-model for pool spread and vaporization. The specification of the source term is a key parameter in determining the gas concentrations and dispersion distances, but is not examined under the MEP or the Advisory Bulletin. However, 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 193.¹⁷

FLACS may be used to model the maximum arc-wise concentration for:

- Dispersion from circularly- or irregularly shaped LNG pools;
- Dispersion from LNG pools with low- and high-aspect ratios (ratio of the surface dimensions of the impoundment), including impoundments and trenches;
- Dispersion from releases in any direction (horizontal, vertical, or otherwise), including releases from flashing, venting, vent stacks, and pressure relief discharge;
- Dispersion from multiple coincident releases, including multiple release locations that may influence each other;
- Dispersion over sloped terrain with a 10% or less grade; and
- Dispersion over obstructions, including large obstructions that may cause wind-channeling and obstructions that may reduce the momentum and subsequent mixing of a high pressure release.

In some cases, FLACS may not be appropriate to model the maximum arc-wise concentration for:

- Dispersion under unstable atmospheric (i.e., A, B, C) stability conditions;
- Dispersion under low ambient pressure (i.e., less than 90 kPa) conditions; or
- Dispersion over varying or sloped terrain with a 10% or greater grade.

The ambient conditions required under 49 C.F.R. § 193.2059 should produce conservative results (i.e., higher downwind gas concentrations and dispersion distances), and therefore the limitation for unstable atmospheric stability conditions and low ambient pressure are not considered as a limitation for 49 C.F.R. § 193.2059 applications.

¹⁷ *In the Matter of Msrs. 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).

The omission of upward slopes or sloped obstructions that span short distances (e.g., berms, swells, etc.) should provide conservative results (i.e., higher downwind gas concentrations and dispersion distances), and therefore is not considered as a limitation for 49 C.F.R. § 193.2059 applications. The inclusion of sloped obstructions that span short distances (e.g., berms, swells, etc.) would be more representative of the validation against obstructions and would not be limited to slopes of 10% or greater.

FLACS should be used with a safety factor of 2 (i.e., ½ LFL) to compensate for uncertainties related to potential turbulent fluctuations, source term specification, wind tunnel experiment validation results, obstructed validation results, sloped validation results, and atmospheric stability validation results.

Environmental Impacts

The National Environmental Policy Act (42 U.S.C. §§ 4321 – 4375) requires Federal agencies to analyze proposed actions to determine whether those actions will have a significant impact on the human environment. Under the Council on Environmental Quality's (CEQ) implementing regulations, Federal agencies must conduct an environmental review that considers (1) the need for the proposed action, (2) alternatives to the proposed action, (3) the probable environmental impacts of the proposed action and alternatives, and (4) the agencies and persons consulted during the consideration process. 40 C.F.R. § 1508.9(b).

1. Purpose and Need

The federal siting standards require an operator or a governmental authority to exercise control over the activities that can occur within an exclusion zone, defined as the area around an LNG facility that could be exposed to unsafe levels of thermal radiation or flammable vapor gas in the event of a release or ignition. Certain mathematical models must be used to calculate the dimensions of these exclusion zones, but alternative models may be used subject to the Administrator's approval.

PHMSA is approving GexCon's Petition to use FLACS as an alternative model under 49 C.F.R. § 193.2059(a). "The intent . . . of providing for the use of alternative models [i]s to permit operators to take advantage of new technical information as it becomes available in developing predictive mathematical dispersion models."¹⁸ FLACS is based on new technical information, and the results of the MEP show that it is suitable for use under 49 C.F.R. § 193.2059(a) in certain scenarios.

2. Alternatives

In arriving at this decision, PHMSA considered two alternatives:

(1) No action or

¹⁸ *In the Matter of Energy Terminal Services Corporation*, PHMSA Interp. 82-05-28 (May 28, 1982).

(2) Approving FLACS for use in calculating the vapor gas dispersion exclusion zone for an LNG facility under 49 C.F.R. § 193.2059(a) where suitable and with limitations.

Alternative 1:

PHMSA has an obligation to ensure that the siting of LNG facilities is consistent with public safety. The information submitted by GexCon shows that approving FLACS for use where suitable and with limitations will accomplish that objective. Failing to approve an alternative model in such circumstances would discourage further improvements and innovation in the field of consequence modeling. FLACS may also be more suitable for use than the currently approved vapor gas dispersion models in certain situations. Accordingly, PHMSA rejected the no action alternative.

Alternative 2:

PHMSA is approving FLACS for use in calculating the vapor gas dispersion exclusion zone for LNG facilities where suitable and with limitations. Such approval ensures that these facilities are sited in a manner consistent with public safety and encourages further innovation and improvements in the field of consequence modeling. FLACS may also be more suitable for use than the currently approved vapor gas dispersion models in certain scenarios.

3. Analysis of Environmental Impacts

There are 11 LNG terminals and over 100 smaller LNG facilities in operation in the United States and Puerto Rico. Unless covered by an exception, any significant alteration or addition to these existing LNG facilities would be subject to the siting requirements in 49 C.F.R. Part 193, and FLACS can potentially be used to calculate the required vapor gas dispersion exclusion zone. There are also 9 proposed and potential LNG terminals and numerous other smaller LNG facilities that might be constructed in the near future. FLACS can potentially be used to calculate the exclusion zones for these new LNG facilities.

The physical environment potentially affected by this decision includes the airspace, water resources (e.g., oceans, streams, lakes), cultural and historical resources (e.g., properties listed on the National Register of Historic Places), biological and ecological resources (e.g., coastal zones, wetlands, plant and animal species and their habitat, forests, grasslands, offshore marine ecosystems), and special ecological resources (e.g., threatened and endangered plant and animal species and their habitat, national and State parklands, biological reserves, wild and scenic rivers) that exist directly adjacent to and within the vicinity of an existing or new LNG facility.

Projections about the demand for natural gas and LNG are based on a wide range of variables that are subject to change. It is also difficult to make predictions about the use and effect of approving a particular vapor gas dispersion model, which depends on a number of site and project specific parameters. It should be further noted that PHMSA does not determine the location of LNG facilities, and that an individualized environmental analysis is performed by FERC and the other state agencies which make those determinations.

4. Consultations

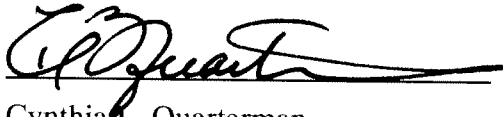
Several other federal agencies, including FERC, were consulted in the development of this decision.

5. Decision about the Degree of Environmental Impact

PHMSA has determined that approving this Petition would not result in significant impact on the human environment.

Conclusion

For the reasons stated in this Final Decision, PHMSA is approving GexCon's Petition to use FLACS as an alternative vapor gas model under 49 C.F.R. § 193.2059(a) where suitable and with certain limitations.



Cynthia L. Quarterman

Date Issued:

Administrator

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