U.S. Department
of Transportation
**Pipeline and Hazardous Materials
Safety Administration**

Administrator

1200 New Jersey Avenue, SE.
Washington, DC 20590

'AUG 1 5 2011

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 Draft Decision on your petition for approval of the FLACS (Version 9.1 Release 2) vapor gas dispersion model. This Draft Decision will be made available for public comment for 30 days before a Final Decision is issued. Service of this Draft 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

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

DRAFT DECISION

GexCon US Inc. (Petitioner or GexCon) has filed a petition for approval (Petition) of FLACS[1] (Version 9.1 Release 2) under 49 C.F.R. §§ 190.9 and 193.2059(a).[2] This Draft Decision proposes to approve that petition and will be made available for public comment for 30 days. Any comments received within that time will be considered before a Final Decision is issued. Late comments will be considered to the extent practicable.

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. On December 3 and 7, 2010, GexCon supplemented its Petition by submitting the remaining portions of the Model Evaluation Report for FLACS.

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.

Background

PHMSA issues federal safety standards for siting LNG facilities.[3] Those standards require that an operator or 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.[4] PHMSA also requires that certain mathematical models be used to calculate the dimensions of these exclusion zones.[5]

Under the current regulations, vapor-gas-dispersion exclusion zones may be calculated using either the DEGADIS Dense Gas Dispersion Model (DEGADIS) or FEM3A.[6] The Administrator 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."[7]

On August 30, 2010, PHMSA issued an Advisory Bulletin with guidance on obtaining approval of alternative vapor gas dispersion models.[8] 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.[9] As the Advisory Bulletin explained:

---

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

[4] 49 C.F.R. § 193.2007 (defining exclusion zone).

[5] 49 C.F.R. §§ 193.2057-2059.

[6] 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 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.").

[7] 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).

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

[9] 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

> 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.[10]

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.

Analysis[11]

Evaluating the suitability of an alternative vapor gas dispersion model is a task that involves "making predictions, within [PHMSA's] area of special expertise."[12] 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).[13] 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

---

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).

[10] 75 Fed. Reg. at 53372.

[11] This analysis relates solely to the use of FLACS under 49 C.F.R. Part 193 and is not intended to authorize or restrict its use in any other applications.

[12] *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.").

[13] *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).

validation. PHMSA has reviewed that information and determined that FLACS may be used to calculate the vapor gas dispersion exclusion zone for an LNG facility in certain scenarios.

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

- Dispersion from circularly-shaped LNG pools;
- Dispersion from LNG pools with low-aspect ratios, including most impoundments;
- Dispersion from horizontally or vertically oriented releases, including releases from flashing, venting, vent stacks, and pressure relief discharge;
- Dispersion from irregularly-shaped LNG pools;
- Dispersion from LNG pools with high-aspect ratios, including some impoundments and nearly all trenches;
- Dispersion from multiple coincident releases, including multiple release locations;
- Dispersion over sloped terrain with a 10% or less grade; and
- Dispersion over obstructions, including large obstructions that may cause wind-channeling.

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 public is invited to comment on each of these conclusions.

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 dust 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 sub-models for flashing and jetting and 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 unnecessarily increase simulation times for scenarios where compressibility is often not relevant (i.e., pool spread and dispersion) without a noticeable increase in solution accuracy. In addition, solving the URANS equations may also unnecessarily increase simulation times for steady state simulations without a noticeable increase in solution accuracy. Although using these approaches increase 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 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 CFR 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 CFR 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, it is recommended 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 CFR 193 applications.

Time discretization

FLACS time steps are specified in terms of the Courant Friedrick 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, a 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 (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 (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 can model multiple concurrent gaseous leak sources and vessel leak sources, as well as one liquid leak source at different locations.

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

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 just 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 is limited to predicting jetting and rainout from horizontal releases. 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 is also currently limited to eight substances, but includes all the major components that constitute typical LNG compositions.

High momentum gaseous jet sources are modeled using a separate built-in sub-model. The sub-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 aftershock is provided for the expanded jet. The 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.

If used, the jet source axis needs to be aligned to the Cartesian mesh and the grid needs to be refined in the area of the jet source. If the grid is not refined and too low of a grid resolution is applied in the jet source cell, the gas concentration is 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 separate 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. 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 should be specified with the lower wind speed that is reflective of the area to produce conservative results. For applications pertinent to this study, FLACS will be used in accordance with 49 CFR Part 193.2059, which specifies the lowest wind speed that occurs 90% of time for the area or 2 m/s. Steady state or periodic wind speed and direction is not expected to be a limitation of the model for 49 CFR Part 193 applications. However, the user should demonstrate the 2 m/s assumption produces the worst case results.

Sloped and varying level terrain

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 by the 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, and 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.

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 CFR Part 193.2059, which specifies the surface roughness of 0.03 m, so this limitation of the model is not a concern.

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. The F stability prescribed in 49 C.F.R. § 193.2059 would generally provide conservative results for LNG releases that disperse over land. 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.

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, 2009[14], Gavelli 2011[15]). FLACS is able to model these wind channeling effects that may occur between adjacent LNG storage tanks, buildings, or large structures. Therefore, there may be cases where obstructions should be included where releases disperse between large adjacent structures.

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.

---

[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.*

The public is invited to comment on each of these conclusions.

Verification

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.

The public is invited to comment on each of these conclusions.

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:

- 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.

FLACS met all of the MEP quantitative acceptance criteria with the exception of maximum arc-wise concentrations for obstructed cases, as shown in Table 1. 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, but under-predictive of maximum arc-wise concentrations for obstructed short time and 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.

However, the MEP specific performance measures and quantitative acceptance criteria are based on an average of all the 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.

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

Table 1 (cont'd):
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 Point-wise Gas Concentration									
Unobstructed Field Trials (Short Time Avg.)	0.92	>1000	2.15	>1000	33%	0.75	N/A	N/A	N/A
Unobstructed Trials (Long Time Avg.)	0.62	31.8	1.40	>1000	50%	1.05	N/A	N/A	N/A
Obstructed Field Trials (Short Time Avg.)	1.34	>100	2.25	>1000	8%	0.31	N/A	N/A	N/A
Obstructed Trials (Long Time Avg.)	0.51	3.47	0.80	>1000	62%	0.74	N/A	N/A	N/A
Unobstructed Wind-Tunnel Tests (Scaled)	0.43	6.53	0.86	>1000	61%	0.85	N/A	N/A	N/A
Obstructed Wind-Tunnel Tests (Scaled)	0.48	46.2	0.95	>1000	56%	0.84	N/A	N/A	N/A
Cloud Width									
Unobstructed Field Trials (Short Time Avg.)	0.76	3.38	1.06	56.30	52%	N/A	N/A	0.54	N/A
Unobstructed Trials (Long Time Avg.)	0.62	2.63	0.88	17.15	63%	N/A	N/A	0.63	N/A
Obstructed Field Trials (Short Time Avg.)	0.57	1.81	0.37	1.51	60%	N/A	N/A	0.57	N/A
Obstructed Trials (Long Time Avg.)	0.23	1.27	0.15	1.17	85%	N/A	N/A	0.82	N/A
Unobstructed Wind-Tunnel Tests (Scaled)	0.17	1.18	0.04	1.04	100%	N/A	N/A	0.85	N/A
Obstructed Wind-Tunnel Tests (Scaled)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

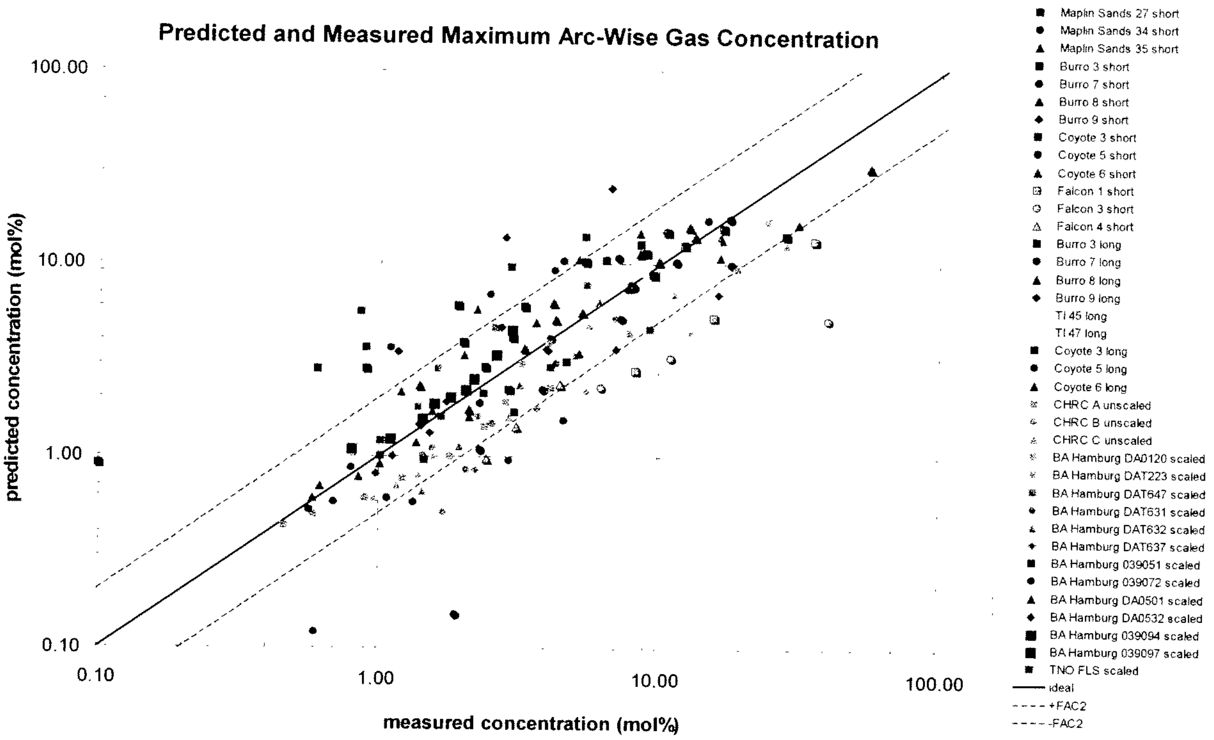

Figure 1 Predicted Concentration against Measured Concentration

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 field trials (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.

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 when evaluating predicted maximum arc-wise concentrations from FLACS for obstructed cases.

FLACS is generally in good agreement or conservative for maximum gas concentration distances with the exception of obstructed field 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. 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 field 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. This may be partly because cloud meander is not a consideration in wind tunnel tests and there are a much larger number of sensors 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 public is invited to comment on each of these conclusions.

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]

FLACS automatically determines the time step based on the CFLC and CFLV criteria specified, and the value is typically on the order of 1/10th 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). In order 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, it is recommended that a grid sensitivity analysis accompanies 49 CFR 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).

The Burro trials used FLACS sinusoidal wind speed functions to more closely match the wind speed of the actual tests, while the other trials used the average wind speed and direction specified in the MEP. A sensitivity test of Maplin Sands 35 and Burro trials indicate lower wind speeds generally produce higher downwind concentrations and dispersion distances, and higher wind speeds produced lower downwind concentrations and dispersion distances.

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 causes the model to under-predict concentrations by a greater margin, but still is within the quantitative acceptance criteria. 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.

A sensitivity test of the Burro and Coyote trials 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. Therefore, the F stability prescribed in 49 C.F.R. § 193.2059 would generally provide conservative results for LNG releases that disperse over land. 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.

Because ambient temperature and surface temperature had little fluctuation, 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.

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.

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.

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.

The public is invited to comment on each of these conclusions.

Model Suitability and Limitations

FLACS has a built-in source term that calculates flashing, jetting, rainout, and pool formation. 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 shaped LNG pools;
- Dispersion from LNG pools with low-aspect ratios, including most impoundments;
- Dispersion from horizontally or vertically oriented releases, including releases from flashing, venting, vent stacks, and pressure relief discharge;
- Dispersion from irregularly shaped LNG pools;
- Dispersion from LNG pools with high-aspect ratios, including some impoundments and nearly all trenches;
- Dispersion from multiple coincident releases, including multiple release locations;
- Dispersion over sloped terrain with a 10% or less grade; and
- Dispersion over obstructions, including large obstructions that may cause wind-channeling.

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.

---

[17] *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).

However, the ambient conditions required under 49 C.F.R. § 193.2059 should produce conservative results (i.e., higher downwind gas concentrations and dispersion distances).

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.

The public is invited to comment on each of these conclusions.

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 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 proposing to approve 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

(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.

---

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

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. It should also be noted that FLACS may 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 proposing to approve FLACS for use in calculating the vapor gas dispersion exclusion zone for LNG facilities where suitable and with limitations. Such approval would ensure that these facilities are sited in a manner consistent with public safety. It would also encourage 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 could 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 could 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.

With that in mind, PHMSA invites public comment on whether either of the alternatives discussed above would result in any significant impacts on the environment.

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 is seeking public comment on whether either of the alternatives discuss above would have a significant impact on the human environment.

Conclusion

For the reasons stated above, I am prepared to approve 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.

This Draft Decision will be made available for public comment for 30 days. Any comments received during that time will be considered before a Final Decision is issued. Late comments will be considered to the extent practicable.

Cynthia L. Quarterman Administrator	AUG 15 2011 Date Issued