Model Validation Database for Flammable Dispersion

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EXECUTIVE SUMMARY

The safe siting of LNG facilities requires the quantification of the consequences to people and property from a loss of containment and release of hazardous materials (e.g., flammable and/or toxic). Calculating the distance to which hazardous conditions may extend for each type of scenario requires the use of computational models.

The quality of models, especially those used to evaluate the consequences of hazardous scenarios on the public or public property, has always been a concern to regulatory bodies. Therefore, the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) funded a research project to develop means to evaluate computational models for the calculations of the different types of hazards associated with the operation of LNG facilities. This research project is being conducted by Blue Engineering and Consulting Company (BLUE), in collaboration with the Gas Technology Institute (GTI).

A general methodology for the evaluation of models was developed and described in an earlier report as part of this project [1]. From the general methodology, a set of hazard-specific model evaluation protocols (MEPs) are developed.

A model validation database (MVD) was previously developed as part of a model evaluation protocol for vapor dispersion from LNG spills (the "LNG spills database" [2], [3]); the same database was used in the evaluation of the Phast and FLACS models by PHMSA in 2011. The scope of the MVD presented in this document is expanded to include pressurized releases and dispersion through complex geometries. The data sets included in the earlier database are also included in the current document, with few exceptions, so that a single database can be used to address all flammable dispersion scenarios typical of LNG facility siting. However, this report provides only a brief summary of those test series; the reader is redirected to the original MVD report for additional information.

The database for flammable dispersion model validation presented in this report includes experimental data from the following test series:

- BA-Hamburg wind tunnel (CO_2, low-momentum release)
- Burro (LNG, spill)
- CHRC wind tunnel (CO_2, low-momentum releases)
- Coyote (LNG, spill)
- Desert Tortoise (Ammonia, flashing jet)
- Falcon (LNG, spill)
- Jack Rabbit II (Chlorine, flashing jet)
- Kit Fox (CO2, low-momentum source)
- Lathen (Propane, flashing jet)
- Maplin Sands (LNG, spill)

1 Structure of the Model Validation Database

Validation is the process of comparing model results to measured data for scenarios that test the physics that the model is intended to predict [4]. In the context of a model evaluation protocol for regulatory purposes, the term "validation" is not intended in absolute terms but, rather, it implies "relative to the scenarios against which it was compared".

Therefore, the purpose of a model validation database is to identify a set of scenarios to be simulated with a computational model, in such a matter that qualitative and/or quantitative comparisons may be made between model predictions and actual observations. In general, the scenarios in the database will consist of experimental data sets; however, real-world scenarios (e.g., accidents) can also be included, provided that there is sufficient information to set up a simulation and evaluate the modeling results.

In addition to specifying data sets for model validation, the MVD needs to include the information necessary to set up and perform the simulations, as well as to define the criteria for comparison of the model predictions with the observations. The following sections describe the different components of the model validation database for flammable dispersion.

1.1 Requirements for Suitable Data Sets

In order to be suitable for the validation of a flammable dispersion model, a dataset should meet the following requirements [5]–[7]:

- The test configuration should be representative of realistic scenarios. For example, the release of a pressurized stream from a small orifice can be representative of many flammable dispersion scenarios typically included in facility siting studies; the dispersion of tracer amounts of gas from the elevated stack, instead, is likely to be less relevant. The scale of the experiment (e.g., release flowrate, dimensions of the test area, etc.) should also be comparable to actual scenarios.
- The tests should be described in sufficient detail for modelers to set up their simulations in an accurate and consistent manner, with as few assumptions as possible.
- Meteorological data (i.e., ambient temperature, humidity, wind speed and atmospheric stability, etc.) should be available from sensors in/near the area of interest. Location and height of sensors should be provided. The resolution should be sufficient to define the atmospheric boundary layer profiles, or those values should be provided in the test series report.
- The test series should include a wide range of meteorological regimes.

- Sensor data should include measurement of the key variables: in the case of atmospheric dispersion experiments, gas concentration measurements must be available; temperature measurements may also be useful.
- Measurements should be of a sufficient quantity to be statistically representative.
- Uncertainty of all measured and derived quantities should be provided, together with a description of the method used to define such uncertainty.
- If the raw data is not provided, the time-averaging applied to the data must be specified. Since the focus of this MVD is on flammable hazards, the data should ideally be available for short time-averages (e.g. of the order of one second)
- The data must be freely available.
- Concentrations should be available at more than one distance downwind, with sufficient lateral resolution to document the spatial structure of the cloud. Vertical resolution should also be included, to define the cloud stratification.

1.2 Dataset grouping

Every experimental data set generally has a well-defined scope which determines the details of the test series, including the material being released, type of release, the scale, type and quantity of instrumentation, etc. In order to optimize the database, the selected data should span a broad range of conditions and should strike a balance between the number of trials included for each type of scenario. Therefore, it is useful to combine different test series into groups with similar characteristics. Grouping the test series will clearly identify which sets of conditions have sufficient data for model validation and which ones will require additional research and a suitable near-term alternative.

The following sets of parameters have been selected for the purpose of grouping flammable dispersion test series:

- Material:
    A. LNG
    B. Flammable (non-LNG)
    C. Non-flammable
- Release Type:
    A. Liquid Spill or low-momentum gas source
    B. Jet (flashing liquid or gas)
- Dispersion Area:
    A. Unobstructed (e.g., “rural”)
    B. Obstructed (e.g., barriers)
    C. Complex Geometry (e.g., “urban” setting, or topography effects)

It should also be noted that no “tracer” gas release experiments are included in this MVD, since those conditions (small release rate, neutrally buoyant release) are not

representative of flammable dispersion scenarios typically required for LNG facility siting. In fact, the measured gas concentrations in tracer release experiments are generally on the order of 1-100 ppm, which is at least two orders of magnitude smaller than the lower flammability limit (LFL) for most hydrocarbons. Tracer gas experiments are, however, representative of toxic releases and will therefore be reviewed for inclusion in the toxic dispersion MVD.

1.3 Dataset rating

Given the complexities associated with performing atmospheric dispersion experiments, particularly at scales typical of industrial facilities, it is unlikely that many experimental test series would meet each of the requirements listed in 1.1. Therefore, each experimental dataset reviewed for potential inclusion in this MVD is "rated" according to several categories, following an approach first introduced by Skjold et al. [8]. The different ratings are then combined into an average score, which informs the selection of data sets for the validation database.

The following categories are used to rate experimental datasets for the flammable dispersion MVD:

- Relevance to actual scenarios: this category evaluates whether the experimental set up replicates flammable dispersion scenarios that are likely to be modeled in an actual hazard analysis. For example, as described above, a pressurized liquid release from a small orifice would be rated highly, whereas a gas release from a tall stack would receive a lower score.
- Material: this category evaluates the relevance of the fluid released during the experiments to those typically evaluated in an actual hazard analysis. For example, spills of LNG or pressurized propane releases would be rated highly, whereas the release of SF_6 or other chemicals not used in LNG facilities would be rated low.
- Scale: this category compares the scale of the experimental set up to typical hazard analysis scenarios. "Scale" should be intended as both the physical dimensions of the test area (i.e., the distance from the source to the measurement stations) and the strength of the source term (i.e., release flowrate). It should be noted that previous MEPs argued that experimental data from all scales should be considered in the validation of a model, as poor performance at small scales could be indicative of a potential problem in the model. However, the purpose of this project is to evaluate models for a very specific type of application, therefore, if a deficiency only manifests itself at small scales it is not considered relevant to the purpose of the evaluation. For this reason, "full" scale trials will be rated higher than reduced scale or wind tunnel tests.
- Repeatability: this category addresses the inherent uncertainty associated with atmospheric dispersion. For example, if a field scale experiment is run just once,

the measurements will be affected by stochastic conditions specific to that run, which cannot easily be quantified; if the same experiment were to be repeated multiple times, an ensemble average of the data could be calculated as well as a measure of the stochastic uncertainty. Typically, field experiments are rarely repeated due to the complexity of ambient conditions; smaller scale experiments (e.g., wind tunnel or laboratory scale) can be repeated more easily and are subject to more controlled ambient conditions.

- Data quality/availability: this category evaluates whether the data publicly available is adequate to evaluate a model's predictions. Data quality considers the type of measurement performed, the instruments used and the sampling rate. Data availability considers the number and placement of sensors, and whether time traces are available or just peak values.

For each category, ratings will range between 0 and 5, as follows:

- 0 = Not Acceptable
- 1 = Poor
- 3 = Acceptable
- 5 = Excellent

A rating of "0" in any one category will eliminate the data set from consideration for the MVD. An average rating of 3 is considered as the acceptability threshold for a test series. However, the average rating is intended as guidance and not as a strict pass/fail criterion. Other considerations, such as the number of trials addressing a given type of scenario, will also factor into the decision of including a given test series in the database.

Each data set reviewed in Section 2 was rated as described above; the rating is reported on the summary page.

1.4 Datasets and Trials Selected for the Flammable Dispersion MVD

A review of available literature and discussions with various LNG safety and atmospheric dispersion experts led to the identification of over 20 experimental test series focused on the dispersion of gas or vapor clouds. A summary description of each test series is provided in Section 2, including ratings and classification, and the information necessary to set up and run model simulations. The test series included in the flammable dispersion database are shown in Table 1-1, grouped by type of release and dispersion area. Test series involving LNG releases are in blue text; non–LNG flammable releases are in red text; and non-flammable releases are shown in green text. The number in parentheses following each test series name represents the number of trials included in the MVD.

Table 1-1. Experimental test series included in the Flammable Dispersion MVD.

	Unobstructed	Obstructed	Complex Geometry
Spill / Low-Momentum	Burro (3) Coyote (3) Maplin Sands (3) BA-Hamburg Wind T. (5) CHRC Wind Tunnel (1)	Falcon (3) BA-Hamburg Wind T. (4) CHRC Wind Tunnel (2)	Kit Fox (8)
Jet	Desert Tortoise (4) Jack Rabbit II (2)	Lathen (7)	Jack Rabbit II (4)

The following observations can be drawn from Table 1-1:

- A large number of dispersion experiments were conducted using non-flammable fluids, which is reasonable given the safety concerns with handling flammable fluids. Nonetheless, tests using the materials of interest (e.g., LNG) are prioritized as they provide a more accurate test of the physical phenomena of interest. For example, the Jack Rabbit I test series evaluated anhydrous ammonia as a potential surrogate for the more hazardous chlorine; however, the test results determined that ammonia was not a suitable surrogate due to the different behavior when released.
- Most of the test series evaluated dispersion over unobstructed areas, which is reasonable because such configuration allows a cleaner evaluation of models, as the cloud behavior is easier to understand; it is also understandable because most of these test series were conducted in the 1980s, when modeling capabilities were limited. However, with the number of CFD models currently available, additional data on the dispersion of releases in the presence of barriers or complex geometries would be beneficial to increase the confidence in the model's ability to simulate realistic scenarios.
- A data gap exists for jet releases and complex geometries, which typically represent the largest number of flammable dispersion scenarios in a siting study.

As shown in Table 1-1, the flammable dispersion MVD includes a total of 49 trials, of which 32 (65%) are spills or low-momentum releases and 17 (35%) are jet releases. Cloud dispersion occurred over flat terrain in 21 trials (43%), whereas 16 trials (33%) included obstructions (e.g., barriers) and 12 trials (24%) included an urban style "complex" geometry. LNG was released in 12 trials (24%) which were all included in the previous

LNG spills MEP; no jet release experiments involved LNG. Ten trials (20%) involved propane releases; the remaining 27 trials (56%) used non-flammable materials.[1]

Table 1-2 lists each of the 49 trials included in the flammable dispersion model validation database. Data from each trial is included in a spreadsheet ("Flammable Dispersion MVD – rev #.xlsx")[2] that accompanies this report; the data includes ambient conditions, source term characteristics, and measured gas concentrations at individual sensors. A second version of the same spreadsheet ("Flammable Dispersion MVD – Scaled – rev #.xlsx") is also made available; this version includes the same trials and data, with the exception of the wind tunnel trials, which are provided at full scale. The "Scaled" version of the spreadsheet is for use by models that cannot simulate dispersion scenarios at small scales.

[1] Several trials released anhydrous ammonia, which is flammable at concentrations between approximately 15 and 28%. However, most measurement stations were located beyond the reach of the flammable cloud, therefore ammonia releases can effectively be considered non-flammable.

[2] The "#" indicates the revision number for the spreadsheet, which may be updated more frequently than this report.

Table 1-2. Experimental trials included in the Flammable Dispersion MVD.

Series	Test No.	Release Type	Fluid	Notes
BA-Hamburg	BAH DA0120	Low-momentum	SF_6	-
	BAH DAT223	Low-momentum	SF_6	-
	BAH 039051	Low-momentum	SF_6	Upwind fence, 19.15 cm radius
	BAH 039072	Low-momentum	SF_6	Upwind fence, 30.64 cm radius
	BAH DA0532	Low-momentum	SF_6	Downwind fence, 19.15 cm radius
	BAH DA0501	Low-momentum	SF_6	Downwind fence, 30.64 cm radius
	BAH DAT647	Low-momentum	SF_6	Sloped, 4.0% down
	BAH DAT632	Low-momentum	SF_6	Sloped, 8.6% down
	BAH DAT637	Low-momentum	SF_6	Sloped, 11.6% down
Burro	BU 3	Spill	LNG	-
	BU 7	Spill	LNG	-
	BU 8	Spill	LNG	-
CHRC	CHRC A	Low-momentum	CO_2	-
	CHRC B	Low-momentum	CO_2	Dike and tank
	CHRC C	Low-momentum	CO_2	Dike
Coyote	CO 3	Spill	LNG	-
	CO 5	Spill	LNG	-
	CO 6	Spill	LNG	-
Desert Tortoise	DT 1	Flashing jet	Ammonia	-
	DT 2	Flashing jet	Ammonia	-
	DT 3	Flashing jet	Ammonia	-
	DT 4	Flashing jet	Ammonia	-
Falcon	FAL 1	Spill	LNG	Barriers around source
	FAL 3	Spill	LNG	Barriers around source
	FAL 4	Spill	LNG	Barriers around source
Goldfish	GF 1	Flashing jet	Hydrogen Fluoride	-
	GF 2	Flashing jet	Hydrogen Fluoride	-

Series	Test No.	Release Type	Fluid	Notes
	GF 3	Flashing jet	Hydrogen Fluoride	-
Jack Rabbit II	JRII 2	Flashing jet	Chlorine	Downward release; Urban array
	JRII 3	Flashing jet	Chlorine	Downward release; Urban array
	JRII 4	Flashing jet	Chlorine	Downward release; Urban array
	JRII 5	Flashing jet	Chlorine	Downward release; Urban array
	JRII 7	Flashing jet	Chlorine	45-deg. down; Reduced array
	JRII 8	Flashing jet	Chlorine	Vertical release; Reduced array
Kit Fox	KF 5-3	Low-momentum	CO_2	Urban array
	KF 5-4	Low-momentum	CO_2	Urban array
	KF 6-4	Low-momentum	CO_2	Urban array
	KF 6-5	Low-momentum	CO_2	Urban array
	KF 6-6	Low-momentum	CO_2	Urban array
	KF 6-9	Low-momentum	CO_2	Urban array
	KF 7-3	Low-momentum	CO_2	Urban array
	KF 8-8	Low-momentum	CO_2	Urban array
Lathen (EEC)	EEC 07	Flashing jet	Propane	Curved barrier
	EEC 08	Flashing jet	Propane	Curved barrier, 50% porous
	EEC 17	Flashing jet	Propane	Curved barrier
	EEC 18	Flashing jet	Propane	Curved barrier, 50% porous
	EEC 54	Flashing jet	Propane	Linear barrier
	EEC 55	Flashing jet	Propane	Linear barrier
	EEC 56	Flashing jet	Propane	Linear barrier, 50% porous
Maplin Sands	MS 27	Spill	LNG	-
	MS 34	Spill	LNG	-
	MS 35	Spill	LNG	-

1.5 Key Physics of Flammable Dispersion Scenarios

Describing the physics of flammable dispersion within the scope of this database is quite complex; in fact, the behavior of the flammable cloud can vary significantly depending on the characteristics of the scenario, including the type of release, the released fluid, and the area over which the flammable cloud disperses. The LNG spills database focused on liquid spills and also included low-momentum ground-level dense gas releases as they produced similar low-lying clouds. In the current database, the scope is expanded to include high-momentum "jet" releases, which are representative of a large number of LNG facility siting scenarios. Even though the evaluation of the source term is part of a separate model evaluation protocol and therefore not included in the flammable dispersion model evaluation, a brief description of the two types of releases considered in this MVD is provided below.

1.5.1 Liquid spills

Liquid spills represent scenarios in which a loss of containment results in the formation of a liquid pool on a surface. This can occur, for example, if a low-pressure liquid storage tank is breached, resulting in a liquid outflow that collects on the ground; or it can occur if a pressurized pipe or vessel is breached, resulting in a flashing liquid spray, part of which may deposit on the ground or collect onto a surface.

The liquid pool is driven by gravity to spread thinner and to follow any slopes towards lower elevations; this behavior is used to direct liquid spills into a liquid conveyance system (a.k.a., a set of trenches) that terminates at an impoundment area, where the liquid can collect.

Vapors are formed above the surface of the liquid pool; the amount of vapor being generated depends on the properties of the spilled material (e.g., the boiling temperature) and the ambient conditions (e.g., the temperature of the substrate beneath the pool). If the boiling temperature is below the substrate temperature, boiling heat transfer generates intense vaporization of the liquid, resulting in large amounts of vapor which is heavier than the surrounding ambient air and therefore forms a dense vapor cloud above the pool. Over time, the substrate cools down thus reducing the rate of heat transfer to the pool and the vapor generation rate. If the boiling temperature of the liquid is above the temperature of the substrate, vapors are still formed but at a lower rate: vapor generation is now driven by diffusion (and non-boiling heat transfer, if the liquid is colder than the substrate) and the resulting cloud tends to be smaller and have a lower gas concentration.

As more vapor is generated, the vapor cloud tends to spread horizontally due to its higher density but remains low to the ground due to its higher density. In the presence of terrain gradients, the cloud may move away from the pool, driven by gravity; more commonly,

however, wind is the mechanism that drives the vapor cloud away from the source. The dispersion of the low-lying, slow-moving cloud is easily affected by obstacles and obstructions, including barriers intended to stop or redirect it away from areas of concern. As the dense cloud is advected, it mixes with ambient air and absorbs heat from the warmer ground. Eventually, the gas concentration within the vapor cloud falls below the lower flammable limit for the spilled material and the flammable dispersion hazard ceases to exist.

1.5.2 Jet releases

Jet releases occur when a pipe or vessel containing a fluid under pressure is breached. If the fluid is liquefied under pressure, the release scenario results in a flashing jet, where a portion of the stream immediately flashes to vapor upon discharge while the rest is atomized into liquid droplets; the liquid droplets tend to evaporate as the jet moves away from the source and entrains air, however, a portion of the liquid droplets may impinge onto a surface (or the ground) before fully evaporating and result in rainout and the formation of a liquid spill.

The air entrainment results in a less dense and generally “taller” cloud than in the case of a liquid spill; additionally, the cloud can carry momentum from the initial jet for some distance. Therefore, while obstacles and obstruction can affect the dispersion of a flammable cloud from a flashing jet release, controlling this type of cloud using barriers is generally more challenging.

If the fluid is in the gas phase before the breach, the release scenario is likely a choked gas flow, since most gas streams in an LNG facility operate above the critical pressure ratio. If the released gas is lighter than air, the cloud tends to rise shortly after the release, as the jet slows down and buoyancy becomes dominant; if the gas is heavier than air, the cloud tends to fall to the ground and spread as described above for a flashing jet release.

1.5.3 Parameters affecting Flammable Cloud Dispersion

The brief descriptions provided above suggest that, while the characteristics of the flammable cloud formation and dispersion can vary significantly from scenario to scenario, the flammable dispersion scenarios are generally affected by the same parameters, such as:

- Thermodynamic properties of the spilled material (boiling point, molecular weight, etc.)
- Release characteristics (release rate, temperature, momentum, liquid fraction, etc.)
- Substrate characteristics (temperature, heat transfer properties)

- Ambient conditions (wind, temperature, humidity)
- Topography and other geometric considerations (barriers, obstructions)

Models applied to flammable dispersion scenarios should therefore include as many of these parameters as possible; however, it is not necessary for all parameters to be included in a model – for example, several widely used models do not include the effects of topography or obstacles, yet their results can frequently be considered conservative and therefore they are still applicable to many scenarios.

1.6 Variables and Physical Comparison Parameters

The quantity most frequently measured during dispersion experiments is the gas concentration in air, which also represents the variable of concern in siting scenarios. However, in some cases the degree of mixing can be inferred from the measurement of other quantities, such as oxygen concentration or gas temperature. These quantities can therefore be measured as an alternative, or a supplement, to gas concentration measurements.

The selection of physical comparison parameters is critical to ensure that model performance is properly evaluated. Based on the prior model evaluation protocols for atmospheric dispersion models, the PCPs for flammable dispersion were selected as specified by Ivings et al. [4]:

1. Maximum point-wise concentration;
2. Maximum arc-wise concentration;
3. Cloud width;
4. Predicted distance to a measured maximum arc-wise concentration;
5. Predicted distance to the LFL concentration;
6. Predicted concentration at the measured distance to the LFL.

1.6.1 Maximum point-wise concentration

Point-wise concentrations are the gas concentrations in air measured at individual sensor locations, processed using a specified averaging time. Frequently, gas concentrations are reported for both short and long time-averages: the short time-average is typically 1 second, while the long time-average is typically equal to the duration of the steady period of the release. The peak value measured at each sensor and for each averaging time is recorded for comparison with the model's prediction at the same location and under the same averaging time.

The use of point-wise concentrations challenges the model's ability to predict the cloud distribution away from the centerline; therefore, it is a more difficult test than the use of arc-wise maximum concentrations (discussed in the next subsection). The use of point-

wise concentrations is also more easily affected by experimental uncertainties, such as wind speed or direction. However, point-wise concentrations provide critical information on the model's performance in obstructed or complex dispersion scenarios, where arc-wise data may lose significance. Point-wise data are the primary means for inputting data into the validation database, upon which all of the other physical performance parameters are automatically calculated.

Therefore, point-wise concentrations are included as a physical comparison parameter to allow a more detailed comparison between measurements and predictions, where appropriate.

1.6.2 Maximum arc-wise concentration

The maximum arc-wise concentration is the maximum concentration (measured or predicted) across an arc, at a given distance from a release. This definition has been interpreted differently in various validation studies, which has caused confusion when evaluating model performances. Throughout this database and model evaluation protocol, maximum arc-wise concentrations will be compared as specified by Ivings et al. [4]: at each arc distance, the maximum arc-wise concentration will be taken as the maximum at the sensors positions (including elevation); it is critical for this approach to be applied consistently to both experimental data and model predictions, or the model performance will be determined incorrectly. This is particularly important for non-CFD models, that calculate the peak concentration at each distance along the cloud centerline and then apply a distribution profile to calculate the concentration off-axis: if the experiment does not include a sensor along the cloud centerline at a given distance, the maximum measured arc-wise concentration should not be compared with the model's centerline prediction at that same distance; instead, the maximum measured concentration should be compared with the maximum of the predicted concentrations at the same off-axis locations as the sensors.

The approach specified by Ivings et al. has the following advantages:

- It tends to result in lower predicted concentrations, which is important given the experimental uncertainty in the measured data. Conversely, using the centerline value as the maximum arc-wise prediction could lead to overprediction of the experimental results and nonconservative statistical performance measures (SPMs).
- It allows the comparison to be made in cases (e.g., the Falcon trials) where sensors are aligned in rows perpendicular to the array centerline rather than in concentric arcs.
- It is consistent with the approach followed in previous model evaluations by PHMSA ([9], [10]) and in earlier dense gas dispersion model evaluation exercises ([5], [11]–[13]).

The use of maximum arc-wise concentrations for model evaluation is generally a simpler test than the use of maximum point-wise concentrations; it is also less dependent on the experimental boundary conditions. Its simplicity makes it useful in assessing the ability of a model to predict the correct decay of concentration with downwind distance.

The maximum arc-wise concentrations are automatically calculated in the spreadsheet based on the maximum point-wise concentrations predicted by the model. It should be noted that, in several cases, sensors were placed along a straight line perpendicular to the release direction or to the expected wind direction, instead of along an arc centered on the release location; for consistency with previous validation efforts, sensors along these lines are treated as if being along the same arc. It should also be noted that, in some trials, the placement of sensors and obstacles or obstructions did not lend itself to a representation by arcs; in such cases, only point-wise comparisons were performed.

1.6.3 Cloud width

Cloud width measures the crosswind spread of the gas, which is affected by a combination of source characteristics (e.g., pool evaporation or pressurized jet), cloud buoyancy (e.g., dense gas slumping), and turbulent mixing (i.e., wind speed and atmospheric stability). Given the discrete number of sensors at each downwind distance, the cloud width cannot be accurately measured by interpolating the available data. Instead, it is calculated using the following formula [4], based on maximum point-wise concentration measurements from the lowest elevation sensors along each arc:

$$\sigma_y^2 = \frac{\sum Cy^2}{\sum C} - \left(\frac{\sum Cy}{\sum C}\right)^2$$

Where:

- σ_y = cloud width at the selected arc distance
- C = maximum long time-averaged concentration at each sensor
- y = crosswind displacement of each sensor

Hanna et al. [14] defined three conditions that must be met before a measured cloud width is determined:

1. There must be at least four sensors on an arc that register long time-averaged concentrations greater than 0.1%
2. The sensor that registers the maximum long time-averaged concentration must not be located at either end of an arc
3. The lateral concentration distribution must not exhibit a bi-modal pattern (i.e., two concentration peaks as shown in Figure 1-1)

The formula listed above is used for any model, including integral models that can calculate the cloud width based on internal crosswind profiles. This approach allows for a consistent comparison across models.

Ivings et al. noted that the use of cloud width as a PCP has been more limited than other parameters; therefore, there is insufficient information to define acceptable criteria for the statistical performance measures calculated based on cloud width. It should also be noted that Hanna et al. [14] described cloud width as a less discriminating test than peak concentration. Finally, it should be noted that the concept of cloud width loses meaning when cloud dispersion is affected by obstacles or complex geometries, which together represent more than half of the trials in this database.

The cloud width at each measurement arc is automatically calculated in the spreadsheet based on the maximum point-wise concentrations predicted by the model, provided the three criteria specified by Hanna et al. are met.

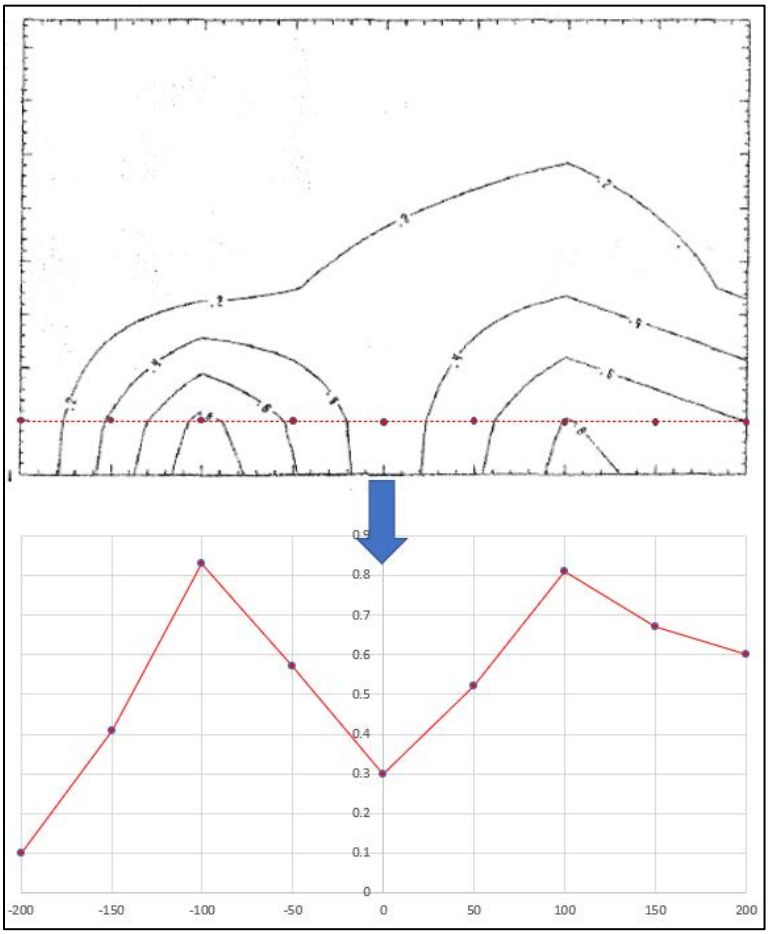

Figure 1-1. Example of bifurcated cloud (above: vertical concentration contours; below: bifurcated curve from sensors measurements at fixed location).

1.6.4 Predicted distance to a measured concentration

The predicted distance to a measured concentration evaluates the ability of the model to accurately predict the distance to a given concentration, as opposed to its ability to accurately predict the concentration at a given distance, as evaluated by the point-wise and arc-wise PCPs.

Given a target concentration, it is unlikely that the predicted value will fall exactly on one of the measurement arc locations. Therefore, data interpolation is required between the maximum arc-wise concentrations predicted at the available arcs. The interpolation is based on a power-law concentration profile:

$$C(x) = Ax^{-B}$$

Where:

- x = downwind distance from the release
- C(x) = predicted maximum arc-wise concentration at distance x
- A, B = power-law constants

The values of A and B are obtained by fitting the power-law profile between the maximum arc-wise concentrations at two consecutive arcs, as shown in Figure 1-2. It is important to note that the power law is fitted between the two arcs that bracket the target concentration, not across the entire cloud concentration profile; therefore, the slope of the curve may not necessarily be continuous across the entire range. It is also important to observe that this approach cannot be applied to extrapolate the curve outside the range of measurement arcs; therefore this PCP can only be calculated for concentrations falling between the measurements along the first and last arc.

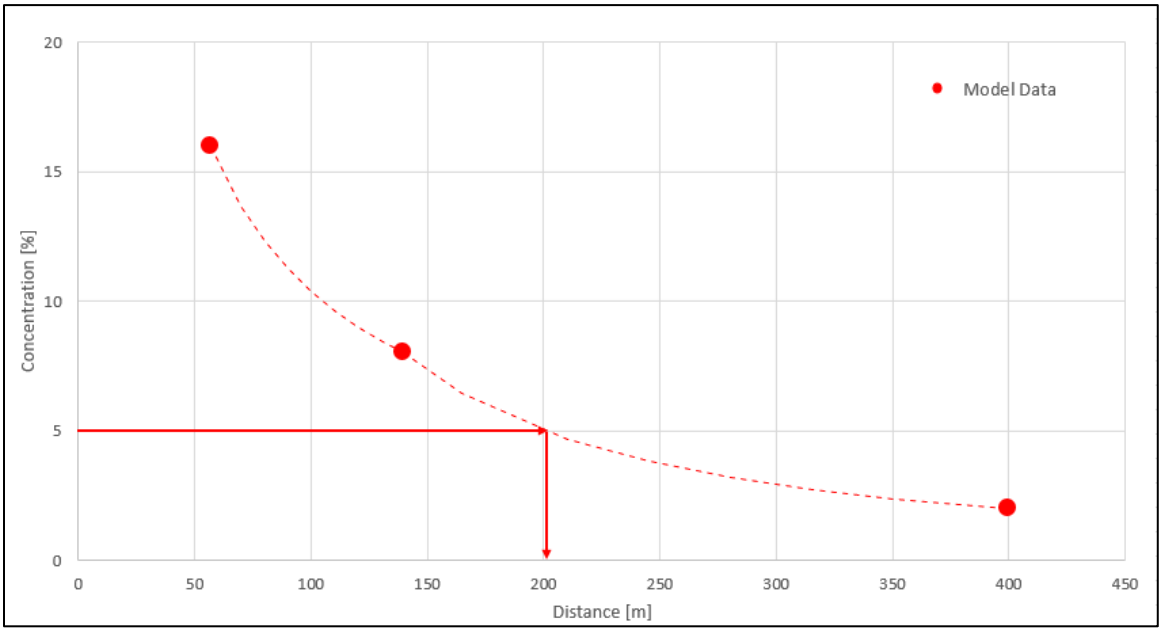

Figure 1-2 Example of power-law interpolation to predicted data.

As discussed for the cloud width PCP, the same interpolation method must be applied for any model type, including those that can directly calculate the distance to a given concentration, in order to have a consistent evaluation approach across all model types.

The predicted distance to a measured concentration is automatically calculated in the spreadsheet based on the maximum point-wise concentrations predicted by the model.

1.6.5 Predicted distance to the LFL concentration

The most obvious choice for a physical comparison parameter based on predicting the distance to a given concentration is the distance to the LFL, since it represents the physical threshold for flammable dispersion hazards (i.e., flash fire). However, one issue with using LFL as the target concentration is that the distance to LFL is unlikely to fall exactly on a measurement arc. Therefore, the power law interpolation discussed in the previous subsection would need to be applied to both the experimental data and the model prediction, as shown in Figure 1-3.

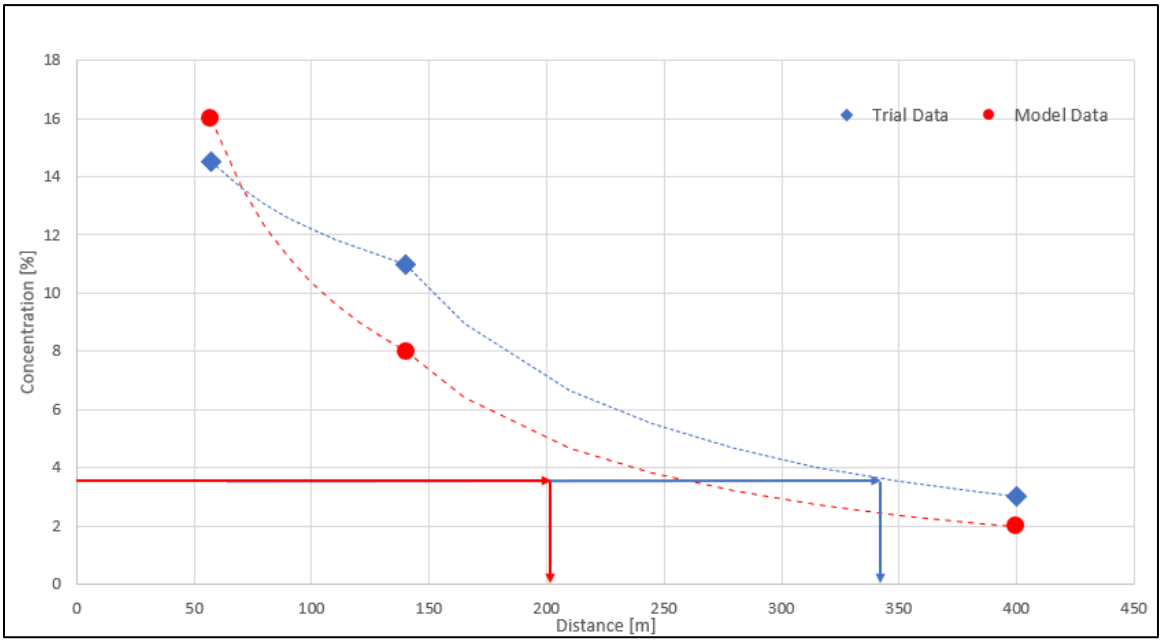

Figure 1-3 Example of power-law interpolation to find the distance to LFL.

A requirement for the applicability of this PCP is that the LFL must fall within the range of both measured and predicted concentrations, otherwise the power-law interpolation cannot be performed. Extrapolating the data to find the distance to LFL outside of the measurement area would introduce significant uncertainty. As previously discussed, the same interpolation method must be applied for any model type, including those that can directly calculate the distance to LFL, in order to have a consistent evaluation approach across all model types.

It is important to note that currently there is insufficient information to define acceptable criteria for the statistical performance measures calculated based on the predicted distance to LFL.

The predicted distance to LFL is automatically calculated in the spreadsheet based on the maximum point-wise concentrations predicted by the model. Several trials in the spreadsheet involved the dispersion of non-flammable materials; in those cases, a target concentration between approximately 1 and 2% was defined as the "LFL equivalent" for the purpose of calculating LFL-related SPMs.

1.6.6 Predicted concentration at the measured distance to the LFL.

The predicted concentration at the measured distance to the LFL is a similar physical comparison parameter to the maximum arc-wise concentration, but uses the measured distance to LFL (obtained by interpolation as described above) instead of a

measurement arc distance. The value of this PCP is that it provides a measure of the over- or under-prediction of the model at the concentration value of most interest when modeling flammable dispersion scenarios.

The predicted concentration at the measured distance to LFL is calculated using the same power law interpolation described in the previous subsections; it is important to point out that only model predictions at the sensor locations can be used in this calculation (i.e., not the centerline values). As previously discussed, the same interpolation method must be applied for any model type, including those that can directly calculate the distance to LFL, in order to have a consistent evaluation approach across all model types.

The predicted concentration at the measured distance to LFL is automatically calculated in the spreadsheet based on the maximum point-wise concentrations predicted by the model.

1.7 Statistical performance measures

Model performance relative to experimental observation can be evaluated on a qualitative and/or quantitative basis.

Qualitative model evaluation consists of comparing predicted and experimental plots of the relevant variables. A qualitative evaluation can be a useful first step in model evaluation as it can provide a general indication of the ability of a model to predict a particular scenario. This procedure can also provide insight on whether a model's behavior is consistent with expectations based on physical understanding of the phenomena involved. Qualitative evaluation should be performed by the model evaluator, and the results should be discussed in the model evaluation report.

The quantitative evaluation consists of defining a set of statistical performance measures (SPMs) that compare predicted and observed physical comparison parameters. The SPMs should be calculated for each available trial as well as for groups of trials with similar characteristics; the calculated SPMs should then be compared to predefined acceptability criteria. Duijm et al. [15] suggested that a suitable set of SPMs should:

- Provide an indication of the model's bias (i.e., whether on average it under- or over-predicts the measurements)
- Provide an indication of the level of scatter (i.e., deviation from the average)
- Give equal weight to all measurements/predictions, regardless of their absolute values

Chang and Hanna [12] suggested that multiple performance measures should be applied as each measure has its advantages and disadvantages. The SPMs should also

be consistent with previous work in order to build on prior experience and increase confidence on the specified acceptability criteria (or revise their values). The statistical performance measures selected to evaluate flammable dispersion models are listed in Table 1-3. The SPMs are automatically calculated in the accompanying spreadsheet, for each trial as well as for groups of trials that fit similar categories as defined in Section1.2.

Table 1-3. Statistical Performance Measures for Flammable Dispersion Models.

SPM	Definition
Mean Relative Bias	$MRB = \langle \frac{c_m - c_p}{\frac{1}{2}(c_m + c_p)} \rangle$
Mean Relative Square Error	$MRSE = \langle \frac{(c_m - c_p)^2}{\frac{1}{4}(c_m + c_p)^2} \rangle$
Fraction of Predictions Within a Factor of 2	$0.5 \leq \left(\frac{c_p}{c_m}\right) \leq 2.0$
Geometric Mean Bias	$GMB = e^{\langle \ln\left(\frac{c_m}{c_p}\right) \rangle}$
Geometric Variance	$GV = e^{\langle \left(\ln\left(\frac{c_m}{c_p}\right)\right)^2 \rangle}$
Concentration Safety Factor	$CSF = \langle \frac{c_p}{c_m} \rangle$
Concentration Safety Factor to the LFL	$CSF_{LFL} = \langle \frac{c_p}{LFL} \rangle$
Distance Safety Factor	$DSF = \langle \frac{x_p}{x_m} \rangle$
Distance Safety Factor to the LFL	$DSF_{LFL} = \langle \frac{x_{p,LFL}}{x_{m,LFL}} \rangle$

1.8 Acceptability criteria

Once the SPMs for a model have been calculated, the quantitative evaluation needs to compare the calculated values to a set of reference values or ranges that define an "acceptable" model.

Acceptability criteria for atmospheric dispersion over unobstructed terrain were first defined by Chang and Hanna [12] and later adopted by Ivings et al. [6]. Only a few models have since been tested against these criteria; therefore, the same acceptability ranges are specified in this MVD. Hanna and Chang [16] later defined a separate set of acceptability criteria for dispersion through an urban environment, recognizing the increased challenge in modeling such scenarios due to the interaction of the cloud with multiple obstacles and obstructions. No models have since been tested against these criteria; therefore, the same acceptability ranges are specified in this MVD.

There is currently no information available to define acceptable values for the more recent SPMs (distance and concentration safety factors). Ivings et al. [4] deemed model predictions to be acceptable if within a factor of two of their respective measurements; therefore, they specified the acceptability range for the distance and concentration safety factors to be the same as for the "fraction of predictions within a factor of 2". For consistency with the earlier protocol, the same acceptability range is specified in this MVD.

It is important to note that all the acceptability criteria previously defined apply to SPMs based on maximum arc-wise concentrations. As discussed in Section 1.6.1, point-wise predictions are generally more challenging; therefore, the acceptability criteria for maximum arc-wise concentrations would be too strict if applied to point-wise predictions. However, given the limited information available on point-wise model comparisons, any relaxation of the acceptability range at this stage would be arbitrary. Therefore, the same stability criteria are applied to point-wise SPMs as to arc-wise SPMs. As more models are evaluated according to this protocol, the acceptability criteria are expected to be reviewed and updated to "not be so stringent that they are not met by most widely used models, and [...] not be so easy that they are met by all models" [12].

The acceptability criteria for the SPMs used in this model evaluation protocol are listed in Table 1-4. Note that "simple" geometry includes unobstructed dispersion as well as dispersion obstructed by a single barrier, whereas "complex" geometry represents dispersion through urban or industrial environments.

It is important to note that the quantitative assessment is just one of several tasks in the model evaluation. Therefore, it is not necessary for a model to meet all SPM acceptability criteria in order to be approved for use. A model falling outside the acceptability range

for one or more SPMs should warrant a closer review in order to understand the cause of such outcome and possibly identify areas for improvement of the model.

Table 1-4. Acceptability Criteria for Flammable Dispersion Model Validation.

Statistical Performance Measure	Arc-Wise, Simple Geometry	Arc-Wise, Complex Geometry	Point-Wise, Simple Geometry	Point-Wise, Complex Geometry
Mean Relative Bias	$\lvert MRB \rvert < 0.4$	$\lvert MRB \rvert < 0.67$	$\lvert MRB \rvert < 0.4$	$\lvert MRB \rvert < 0.67$
Mean Relative Square Error	$MRSE < 2.3$	$MRSE < 6.0$	$MRSE < 2.3$	$MRSE < 6.0$
Fraction of Predictions Within a Factor of 2	$0.5 \leq FAC2$	$0.3 \leq FAC2$	$0.5 \leq FAC2$	$0.3 \leq FAC2$
Geometric Mean Bias	$0.67 < MG < 1.5$	$0.5 < MG < 2.0$	$0.67 < MG < 1.5$	$0.5 < MG < 2.0$
Geometric Variance	$VG < 3.3$	$VG < 7.5$	$VG < 3.3$	$VG < 7.5$
Concentration Safety Factor	$0.5 < CSF < 2$	$0.5 < CSF < 2$	$0.5 < CSF < 2$	$0.5 < CSF < 2$
Concentration Safety Factor to the LFL	$0.5 < CSF_{LFL} < 2$	$0.5 < CSF_{LFL} < 2$	$0.5 < CSF_{LFL} < 2$	$0.5 < CSF_{LFL} < 2$
Distance Safety Factor	$0.5 < DSF < 2$	$0.5 < DSF < 2$	$0.5 < DSF < 2$	$0.5 < DSF < 2$
Distance Safety Factor to the LFL	$0.5 < DSF_{LFL} < 2$	$0.5 < DSF_{LFL} < 2$	$0.5 < DSF_{LFL} < 2$	$0.5 < DSF_{LFL} < 2$

1.9 Data processing

Processing the data from an experiment can be quite complicated. Available experimental datasets vary widely in terms of available instrumentation, measurement frequency, data format (electronic data exists for more recent experiments, but for older experiments only printed traces may be available), etc. Therefore, significant effort may be required in order to convert the data into a format suitable for model evaluation. The procedure used to analyze and process the data should be properly documented so that the process may be replicated. Because of the importance of data processing, guidance was provided in many of the existing protocols; additionally, in some cases, the

experimental data may have already been analyzed and reduced during earlier database development efforts (e.g., MDA [14], REDIPHEM [17], LNG spills [2]). The current model validation database relies upon these earlier efforts wherever appropriate, in order to avoid unnecessary work and potentially inconsistent outcomes.

1.9.1 Threshold Concentrations for Data Analysis

A common issue in the analysis of experimental data is the treatment of "zero" values. When considering SPMs based on the ratio of predicted to measured values (for example, the concentration safety factor c_p/c_m), as the measured value tends to zero that result becomes very sensitive to measurement uncertainties. Since concentration values approaching zero are well below the range of interest in this database (LFL values for the fluids of interest are on the order of approximately 1-5%) as well as close to the limit of detection for many sensors, the concern is that the overall performance of a model could be significantly impacted by data points of limited relevance. In the LNG spills database, for example, 0.1% v/v was set as the minimum measured gas concentration required for a sensor to be included in the SPM calculations. Several of the test series reviewed for this study utilized instruments calibrated for gas concentrations below 1,000 ppm; therefore, the minimum threshold for measured data to be included in the SPM calculations is lowered to 0.01% v/v (1,000 ppm). It should be noted that all measured point-wise maximum concentrations (even those below the threshold) are included in the spreadsheet as reported.

1.9.2 Averaging Times

Flammable cloud dispersion hazards (i.e., flash fires following the ignition of the cloud) are "instantaneous" – that is, ignition can occur if the flammable concentration is present at the same time and place as an ignition source, regardless of whether the flammable concentration was present prior to the ignition source. This is different from toxic hazards, which require a hazardous concentration to be present at a given location for certain time before the consequences of exposure can manifest. Therefore, data from flammable dispersion experiments should include values based on short time averaging which are able to capture short-lived fluctuations in the cloud shape and concentration.

Some models however cannot calculate atmospheric dispersion based on short time averaging: integral models for example use dispersion coefficients based on averaging times on the order of 20 seconds or greater; even many CFD models produce results that are consistent with long averaging times. Therefore, experimental results for each trial in this database are provided based on both short and long time averaging, with the exception of wind tunnel trials that only include long time averaging data.

Most of the trials in the flammable dispersion MVD have a short averaging time of 1 second. The long averaging time is set for each trial to the duration of the steady

portion of the release. In this database, the maximum measured point-wise concentrations are obtained from rolling averages of the available data (typically at 1 Hz frequencies) using the long averaging times.

Whenever possible, model results should be provided for both short and long averaging times, and those averaging times should match the respective experimental values. The accompanying spreadsheet allows both short and long time-averaging data as well as the respective averaging times to be entered for each trial. If the averaging times used in the modeling do not match the experimental values, a discussion should be provided.

The SPMs for the PCPs described in Section 1.6 are calculated for both short and long averaging times, with the exception of cloud width, which is only calculated for long averaging times. When model predictions are provided for both short and long averaging times, the SPMs based on short averaging times should be given more weight in the evaluation, since flammable dispersion hazards do not require prolonged exposure to manifest.

1.10 Sensitivity Analysis

Several methods are available to evaluate uncertainty and sensitivity of models, as discussed by Hanna [18] for atmospheric dispersion models. Some of these methods can require significant effort in order to provide detailed evaluations of a model's performance. For the purpose of this MVD, and of the databases that will be developed for other types of hazards as part of the current project, the sensitivity of model predictions to uncertainty in the input parameters is evaluated according to the requirements in PHMSA Advisory Bulletin ADB-10-07 [19], which specifies that model uncertainty analysis should address:

1. Source term
2. Boundary conditions
3. Wind profile
4. Sub-models
5. Temporal discretization/averaging
6. Spatial discretization and grid resolution
7. Geometry representation

1.10.1.1 Source Term

Even though most scenarios required for facility siting involve releases of liquids under pressure, most atmospheric dispersion models require the source term to be specified as a gas at ambient pressure, whose temperature, composition, flow rate and momentum depend on the characteristics of the release (e.g., liquid pool on the ground, flashing jet, etc.). Therefore, many current models include source term packages that can calculate

the flashing, rainout, air entrainment and evaporation of a jet, the spreading and evaporation of a liquid spill, etc. Models that include such packages should apply them in the "base" simulation, since it is expected that the same packages will be used in facility siting studies. Some of the trials included in this database may also specify sensitivity cases to be run using alternative source term models (e.g., fixed radius pool with given evaporation rate) in order to evaluate the sensitivity of the model to the source term characteristics. Similarly, the nominal release rate reported for each experiment will define the base case; sensitivity cases to the release rate may be added to address uncertainties in the flow rate measurements.

Source term uncertainties may also be due to the properties of the species used in the experiment. For example, sensitivity to the composition of the release is included for trials involving LNG releases: the base case is defined considering the actual stream composition, whereas the sensitivity case approximates LNG as pure methane. For models which require a vapor source term to be specified, the effect of composition can be evaluated by changing the molecular weight of the vapors; models which calculate the pool vaporization internally should modify all relevant material properties to match the given composition.

1.10.1.2 Boundary Conditions

Boundary conditions for atmospheric dispersion modeling include wall properties (e.g., no-slip), and in conditions (e.g., temperature, pressure, relative humidity), surface roughness, and the placement of computational domain boundaries (for CFD models). Nominal values for the boundary conditions are specified in the base case for each trial; sensitivity cases are specified for some trials, where uncertainty in the values of some parameters is considered likely to affect the model predictions appreciably. The boundary condition parameter most likely to warrant a sensitivity study is the surface roughness, which is often affected by significant uncertainty and whose variations tend to significantly affect gas dispersion.

Ambient temperature tends to have a minor effect on the dispersion of gas clouds, especially when compared to other parameters such as wind speed or atmospheric stability. Therefore, evaluating sensitivity to ambient temperature is not warranted unless significant fluctuations are observed during a trial.

Ambient pressure fluctuations tend to have a minor effect on the dispersion of gas clouds, especially when compared to other parameters such as wind speed or atmospheric stability. However, since siting studies typically assume standard atmospheric pressure, FERC included in their review of DEGADIS [20] sensitivity cases to ambient pressure for trials in which the reported pressure was not 1 atmosphere, in order to determine the sensitivity of the model to this assumption.

Relative humidity may affect the dispersion of vapor clouds, especially from cryogenic releases, as the cold vapor temperatures cause the condensation of water vapor into droplets ("fog"), which later re-evaporate as the cloud is diluted and warmed up. Most dispersion models currently available, however, cannot account for the water condensation/evaporation; rather, models are limited to adjusting the density of moist air according to the specified ambient relative humidity. Similar to temperature and pressure, relative humidity has a minor effect on cloud dispersion, particularly at long distances from the source. Therefore, evaluating sensitivity to relative humidity is not warranted unless significant differences are found in the reported data.

The placement and definition of computational domain boundaries for CFD models can also have a significant effect on the modeling results. Given the multitude of possible approaches, the proper definition of domain boundaries for each trial is left to the modelers; however, this does not preclude the model evaluator from requesting sensitivity cases to be performed during the review.

1.10.1.3 Wind Profile

In most cases of interest for flammable dispersion scenarios for LNG facility siting, the flammable cloud tends to be heavier than air and close to the ground. Therefore, once the momentum from the release (e.g., in the case of pressurized jet) has dissipated, the behavior of the cloud is determined by the wind profile near the ground and the topography.

The wind profile near the ground is characterized by gradients of velocity and turbulence, which are functions of several parameters including the roughness of the terrain, the wind speed at elevation, cloud cover, etc.

1.10.1.4 Sub-Models

Models used for atmospheric dispersion studies may include several sub-models, such as the source term packages described above, turbulence closure models, or other solvers designed to increase accuracy or performance in specific scenarios. Given the large number of existing sub-models and their respective parameters, this MVD does not include specific sensitivity cases to evaluate their effect on model predictions. The base case for each model should include the most appropriate sub-models, as they are expected to be used in actual facility siting studies; the choice of sub-models and specific parameters used should be described and explained in the model evaluation report. Sensitivity cases may be included for additional information or may be requested by the model evaluator.

1.10.1.5 Temporal discretization/averaging

As discussed in Section1.9.2, each trial in this MVD includes experimental data based on specified averaging times. Models should be run using averaging times equal to or shorter than the experimental values listed in this database; the averaging times used in the modeling should be specified in the spreadsheet. If a model cannot be run with averaging times as specified above, sensitivity cases to different averaging times should be included.

1.10.1.6 Spatial discretization and grid resolution

Certain types of models perform their calculations onto a grid of discrete points, whose spacing can be specified by the user. Given the different types of models available for flammable dispersion, a grid sensitivity study is not explicitly required in this MVD. Instead, modelers are considered responsible for selecting a "grid independent" spacing for their model, for each trial, and running the "base" case and any other sensitivity case using the same spacing. Additional information, including grid sensitivity cases or evidence of grid convergence, may be requested by the model evaluator.

1.10.1.7 Geometry representation

Most of the trials in this MVD include flat or nearly flat terrain; the placement and dimensions of all obstacles (barriers, containers) is clearly defined in this report, the accompanying spreadsheet, or test specific references. Therefore, the main cause of uncertainty with regards to geometry representation is the terrain profile in a few cases (e.g., the Burro 8 trial) where, in previous modeling, topography was found to affect the dispersion of dense gas clouds due to low wind speeds.

For this reason, and to provide consistent boundary conditions for all types of models, the base case for all trials included in this MVD assumes flat terrain. Sensitivity cases may be run to evaluate the effects of topography in models with such capabilities.

1.11 Use of the Database

The model validation database for flammable dispersion consists of the present report and of a spreadsheet (in Microsoft Excel format). The report provides background information on the model validation activities, as well as a description of each data set included in the database. The model developer (or anyone interested in comparing a model to experimental data) should review these documents, and possibly some of the cited references, prior to commencing any simulations.

The spreadsheet includes a sheet for each individual trial, which summarizes the relevant information necessary to set up simulations, such as:

- Overall description, including barriers and other obstacles
- Source term (material properties, flowrate, release location, etc.)
- Sensor location and maximum measured concentration for short and long averaging times
- Boundary conditions (wind speed and direction, temperature, surface roughness, etc.)
- Material properties for the released species, for use with models that do not include that species (or mixture) in their database. The material properties were calculated using the REFPROP database[3]

Each sheet is locked for editing, with the exception of cells highlighted in orange, which are intended for user input: the user should enter model information, scenario characteristics (e.g., for user-selected sensitivity cases) and the modeling results for the base case and the sensitivity cases. The spreadsheet will automatically generate plots to visually compare the model predictions to the measurements; it will also automatically calculate the model uncertainty and the statistical performance measures for each trial. Each sheet is laid out to print in an organized and consistent pattern on "Letter" size pages (however, printing the spreadsheet results is not required).

A set of summary sheets is also included in the spreadsheet. These present the SPM calculations for the entire database, as well as for groups of trials with similar characteristics (e.g., jet releases over unobstructed terrain), to aid in the model evaluation.

[3] https://www.nist.gov/srd/refprop

2 Model Validation Datasets

The scope of the present database includes a wide variety of scenarios, as described by the groupings in Section 1.2. In order to identify suitable data sets for each of the groupings, the project team reviewed several resources and reached out to various entities including:

- Modeler's Data Archive [12], [21];
- REDIPHEM database [22], [23];
- SMEDIS database [11], [24];
- LNG spills database [2], [3];
- Jack Rabbit I and Jack Rabbit II test series [25]–[28];
- Various research and testing organizations.

Each of the test series reviewed for this MVD is listed in the following subsections:

1. A brief description of the test series
2. The grouping and rating of the experiments according to the criteria in Sections 1.2 and 1.3, respectively.

For the test series that are included in the MVD, additional information is provided, such as:

3. Test series observations and comments: it includes any particular observations or comments on specific trials that may be of interest for modeling purposes. It also provides a list of the trials included in the MVD, with a summary of the main parameters (e.g., source term, wind, obstacles, etc.).
4. Ambient conditions: it describes the type and placement of instruments to measure temperature, wind speed and direction, atmospheric stability, etc. Information regarding the sampling rate and accuracy of the instruments is also included, when available.
5. Discharge system: it describes the fluid storage and release system, and associated instrumentation.
6. Dispersion area: it describes the characteristics of the terrain over which the released cloud dispersed, including slopes, obstacles and obstructions that may affect the behavior of the cloud.
7. Gas measurement instrumentation: it describes the type and placement of instruments to measure gas concentration and other variables that may be used to compare against model "outputs". Information regarding the sampling rate and accuracy of the instruments is also included, when available.
8. Time averaging: it sets the averaging times for short- and long-time averaging for each trial, to be used by the modelers for a proper comparison with the experimental data.

9. Experimental uncertainty: it describes the sampling rate and accuracy of the instruments, when available. When this information is not available, estimates are provided and identified as such. These values will be used in the model validation spreadsheet to define experimental uncertainty bands in the model comparison plots.
10. Sensitivity cases: it specifies a minimum set of sensitivity cases to be modeled, in addition to the "base" case, to evaluate the effect on results from uncertainty in the source term or boundary conditions.

The purpose of the following subsections, coupled with the accompanying spreadsheet, is to provide modelers with sufficient information to set up the simulations. Several references are provided for each test series, where additional information may be obtained by interested readers.

Several of the test series included in this MVD (i.e., Burro, Coyote, Falcon, Maplin Sands, BA-Hamburg and CHRC) were previously included in the "LNG spills" database by Stewart et al. [3], who provided a review and description of each series for model evaluation. Therefore, only a brief description of those series is included in this MVD; the readers are directed to the cited report (or other test-specific references) for additional information.

2.1 BA-Hamburg and BA-TNO Wind Tunnels

Experimental campaign	BA-Hamburg (BAH) and BA-TNO (TNO)
Test dates:	N/A
Number of trials:	146 (BAH); 13 (TNO)
Test location:	University of Hamburg and TNO wind tunnels
Tests performed by:	University of Hamburg and TNO
Brief description:	Sulfur hexafluoride gas release in a wind tunnel. Dispersion over different sets of obstacles.
References:	Stewart et al., 2016 [3] Nielsen and Ott, 1996 [23]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Low-momentum
Dispersion Area:	Unobstructed; Obstructed
Test series rating	
Overall:	**3.0**
Relevance:	4
Material:	2
Scale:	1
Repeatability:	4
Data Quality/Availability:	4

2.1.1 Description

The BA-Hamburg and BA-TNO test series consisted of sulfur hexafluoride (SF_6) gas releases in wind tunnels; they were conducted at the Meteorological Institute at the University of Hamburg in Germany and at the TNO 'Pollution Industrial Aerodynamics' wind tunnel facility. The source term consisted of a ground-level release through a circular opening, resulting in a low-velocity vertical flow through the wind tunnel floor. Both instantaneous and continuous releases were performed. Different downwind configurations were tested, including unobstructed (flat and sloped floor) and obstructed cases. Figure 2-1 shows a schematic of the BA-Hamburg tests.

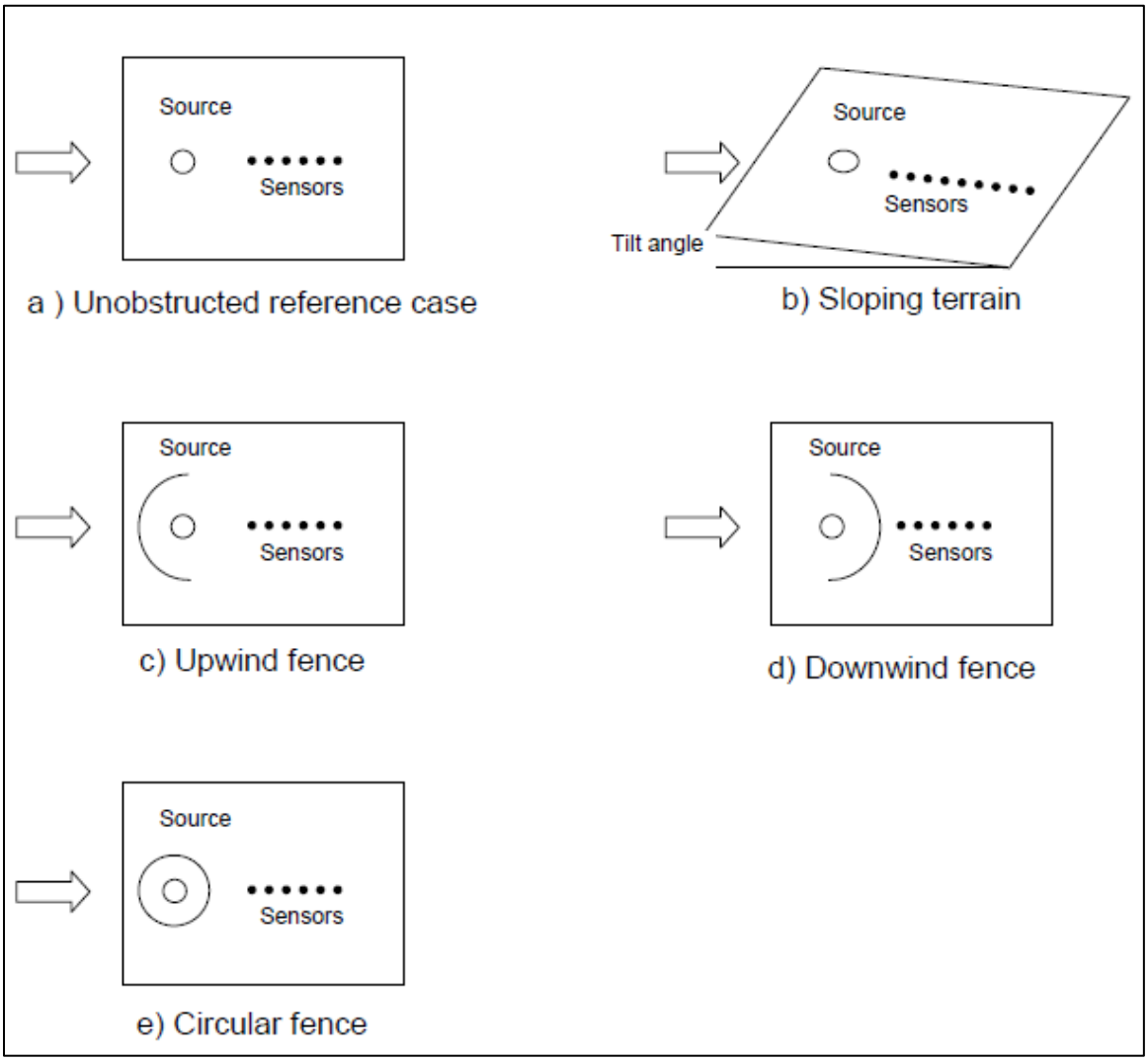

Figure 2-1. BA-Hamburg test configurations [3].

The University of Hamburg wind tunnel consisted of a 7.5 m long flow establishment section and a 4 m long test section; air flow was pulled through the test section by a centrifugal fan near the exhaust. The test section was 1.5 m wide and 1 m high. The experiments were set up for a scale of 1:164. SF_6 was introduced through a 7 cm diameter perforated disk, flush with the tunnel floor. The obstructions consisted of 3.01 cm tall barriers, with radius of 19.15 cm or 30.64 cm depending on the trial.

The TNO wind tunnel was 16 m long and consisted of a 10 m long flow establishment section and a 6.8 m long test section; flow was pulled through the test section by a centrifugal fan near the exhaust. The test section was 2.65 m wide and 1.2 m high. The experiments were set up for a scale of 1:78. SF_6 was introduced through a 10.7 cm diameter perforated disk, flush with the tunnel floor. Trial TUV02 included a fence 0.615 m downwind from the release, 0.256 m tall and 0.64 m long.

2.1.2 Test Series Grouping and Rating

The BA trials consisted of low-momentum, continuous releases of SF_6 through the floor of a wind tunnel. The resulting clouds were advected through the wind tunnel and dispersed over different configurations – both unobstructed (flat or sloped) and obstructed (straight or circular barriers). The test series therefore fit in the following categories:

- Material: Non-flammable
- Release Type: Low-momentum
- Dispersion Area: Unobstructed; Obstructed

The ground-level source term is representative of vapor generation from an evaporating liquid pool, and the presence of obstacles upwind or downwind of the release is quite common in LNG facilities; therefore, the scenarios modeled in the BA trials are relevant siting studies (“Relevance” rating = 4). Sulphur hexafluoride is not a material used in LNG facilities or present in feed gas; however, the use of SF_6 as a gas to produce dense clouds in wind tunnel trials is well-established (“Material” rating = 2).

Wind tunnel tests are performed at a scale much smaller than actual plants. While this has benefits in terms of costs and controllability of boundary conditions, the reduced scale tends to increase the effect of near-wall phenomena on the overall behavior of the cloud, which in turn may affect the model’s performance for reasons not relevant to its intended applications. Therefore, the scale of wind tunnel trials is considered a poor fit for this MVD (“Scale” rating = 1).

Wind tunnel trials allow the source term and boundary conditions to be finely controlled, allowing for steady state conditions to be achieved and sustained for long periods of time. Therefore, the repeatability of the experiments is good (“Repeatability” rating = 4).

The overall quality and availability of data is considered more than acceptable for the purpose of this MVD ("Data quality/availability" rating = 4).

Overall, the BA-Hamburg and BA-TNO series are rated at 3.0, which meets the "acceptable" threshold; therefore, the test series are considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the BA-Hamburg and BA-TNO series in the MVD for LNG spills [3].

2.1.3 Test Series Observations and Comments

Several trials from both BA-Hamburg and BA-TNO were included in the model validation database for LNG spills by Stewart et al. [3]. Several of those trials are also included in the current MVD to provide continuity for models previously evaluated against the LNG spills database; however, in order to balance the number of low-momentum and jet releases, only 9 of the 12 BA-Hamburg trials from the LNG spills database are included in this MVD and no BA-TNO trials are included.

Table 2-1 lists the main characteristics for the trials included in the flammable dispersion MVDs. The values provided in the table are at wind tunnel scale. Some models may be unable to perform simulations at these scales; therefore, for each wind tunnel trial, the accompanying spreadsheet also includes data at full scale. The wind tunnel scale remains the preferred option for models capable of simulating small scales.

Table 2-1. BA-Hamburg test characteristics.

Test No.	Release Rate [kg/s]	Wind Speed [m/s]	Obstruction
BAH-DA0120	1.74E-4	0.54 @ 7.2 mm	-
BAH-DAT223	8.72E-4	0.74 @ 7.2 mm	-
BAH-039051	8.72E-4	0.74 @ 7.2 mm	Upwind fence, 19.15 cm radius
BAH-039072	8.72E-4	0.74 @ 7.2 mm	Upwind fence, 30.64 cm radius
BAH-DA0532	8.72E-4	0.74 @ 7.2 mm	Downwind fence, 19.15 cm radius
BAH-DA0501	8.72E-4	0.74 @ 7.2 mm	Downwind fence, 30.64 cm radius
BAH-DAT647	1.74E-4	0.0	Sloped, 4.0% down
BAH-DAT632	1.74E-4	0.0	Sloped, 8.6% down
BAH-DAT637	1.74E-4	0.0	Sloped, 11.6% down

The thermodynamic properties of SF_6 needed for dispersion modeling are included in the MVD spreadsheet for each trial. These values should be used in models which do not have a species database, or which do not include the released material.

2.1.4 Time Averaging

The BA-Hamburg wind tunnel trials were run to steady state; therefore, the concept of averaging time is not as critical as in a transient scenario and, with the possible exception of the initial and final transients, short- and long-time averaging should provide the same results. Therefore, only long time averages are considered for the wind tunnel trials. The averaging times, as provided by Stewart et al., are listed in Table 2-2.

Table 2-2. Averaging times for the BA-Hamburg trials.

Trial	Long time avg.
BAH-DA0120	225 s
BAH-DAT223	80 s
BAH-039051	225 s
BAH-039072	225 s
BAH-DA0532	160 s
BAH-DA0501	160 s
BAH-DAT647	90 s
BAH-DAT632	58 s
BAH-DAT637	40 s

2.1.5 Test Series Sensitivity Cases

The BA-Hamburg trials were conducted under well controlled and steady atmospheric conditions, and with well-defined source terms, as is typical of wind tunnel experiments. Sensitivity analyses relative to atmospheric conditions or source term are generally not warranted for wind tunnel trials; however, Stewart et al. [3] suggested that models may require different surface roughness values in order to produce velocity and turbulence profiles consistent with the wind tunnel measurements [20][20].

2.1.5.1 Roughness Length

Stewart et al. reported a nominal value of 0.033 mm for the roughness length of the wind tunnel floor; additionally, they specified an uncertainty range of ±0.027 mm within which

models should be evaluated to find an adequate match to the experimental velocity and turbulence profiles. The same uncertainty range is used to specify sensitivity cases for the BA-Hamburg wind tunnel trials in this MVD.

2.1.5.2 Summary of Sensitivity Cases

Table 2-3 through Table 2-5 summarize the source parameters and ambient conditions for the BA-Hamburg trials in the MVD, respectively. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the MDA database and the database developed by Stewart et al. [3], which is available upon request to the Fire Protection Research Foundation. Additional information on these trials can be found in the references listed in the summary table.

Table 2-3. Base and sensitivity cases for the BA-Hamburg trials in the MVD (1/3).

Parameter	Case	BAH-DA0120	BAH-DAT223	BAH-039051
Source term	Base	Low-momentum ground level injection	Low-momentum ground level injection	Low-momentum ground level injection
Release Rate	Base	1.74E-4 kg/s	8.72E-4 kg/s	8.72E-4 kg/s
Release Duration	Base	Continuous	Continuous	Continuous
Wind Speed (at 7.18E-3 m height)	Base	0.54 m/s	0.74 m/s	0.74 m/s
Surface Roughness Length	Base	3.3E-5 m	3.3E-5 m	3.3E-5 m
	R1	6.0E-5 m	6.0E-5 m	6.0E-5 m
	R2	6.0E-6 m	6.0E-6 m	6.0E-6 m
Atmospheric Stability	Base	D	D	D
Ambient Temperature	Base	14.0 °C	14.0 °C	14.0 °C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	N/A	N/A	N/A
Stream Composition	Base	SF_6 = 100%	SF_6 = 100%	SF_6 = 100%

Table 2-4. Base and sensitivity cases for the BA-Hamburg trials in the MVD (2/3).

Parameter	Case	BAH-039072	BAH-DA0532	BAH-DA0501
Source term	Base	Low-momentum ground level injection	Low-momentum ground level injection	Low-momentum ground level injection
Release Rate	Base	8.72E-4 kg/s	8.72E-4 kg/s	8.72E-4 kg/s
Release Duration	Base	Continuous	Continuous	Continuous
Wind Speed (at 7.18E-3 m height)	Base	0.74 m/s	0.74 m/s	0.74 m/s
Surface Roughness Length	Base	3.3E-5 m	3.3E-5 m	3.3E-5 m
	R1	6.0E-5 m	6.0E-5 m	6.0E-5 m
	R2	6.0E-6 m	6.0E-6 m	6.0E-6 m
Atmospheric Stability	Base	D	D	D
Ambient Temperature	Base	14.0 °C	14.0 °C	14.0 °C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	N/A	N/A	N/A
Stream Composition	Base	SF_6 = 100%	SF_6 = 100%	SF_6 = 100%

Table 2-5. Base and sensitivity cases for the BA-Hamburg trials in the MVD (3/3).

Parameter	Case	BAH-DAT647	BAH-DAT632	BAH-DAT637
Source term	Base	Low-momentum ground level injection	Low-momentum ground level injection	Low-momentum ground level injection
Release Rate	Base	1.74E-4 kg/s	1.74E-4 kg/s	1.74E-4 kg/s
Release Duration	Base	Continuous	Continuous	Continuous
Wind Speed (at 7.18E-3 m height)	Base	0.0 m/s	0.0 m/s	0.0 m/s
Surface Roughness Length	Base	3.3E-5 m	3.3E-5 m	3.3E-5 m
	R1	6.0E-5 m	6.0E-5 m	6.0E-5 m
	R2	6.0E-6 m	6.0E-6 m	6.0E-6 m
Atmospheric Stability	Base	D	D	D
Ambient Temperature	Base	14.0 °C	14.0 °C	14.0 °C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	N/A	N/A	N/A
Stream Composition	Base	SF_6 = 100%	SF_6 = 100%	SF_6 = 100%

2.2 Burro

Experimental campaign	Burro (BU)
Test dates:	1980
Test location:	China Lake, California
Number of tests:	8
Tests performed by:	Naval Weapons Center and Lawrence Livermore National Laboratory
Brief description:	LNG spills onto water; unobstructed vapor cloud dispersion over land.
References:	Stewart et al., 2016 [3] Koopman et al., 1982 [29], [30] Ermak et al., 1983 [31] Ermak et al., 1989 [32]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	LNG
Release Type:	Spill
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**4.0**
Relevance:	5
Material:	5
Scale:	5
Repeatability:	2
Data Quality/Availability:	3

2.2.1 Description

The Burro test series consisted of 8 spills of LNG onto water; they were conducted at the Naval Weapons Center at China Lake. The vapor clouds produced by the evaporation of the liquid spills dispersed over mostly flat terrain[4]. Figure 2-2 shows a schematic of the spill area and measurement arcs.

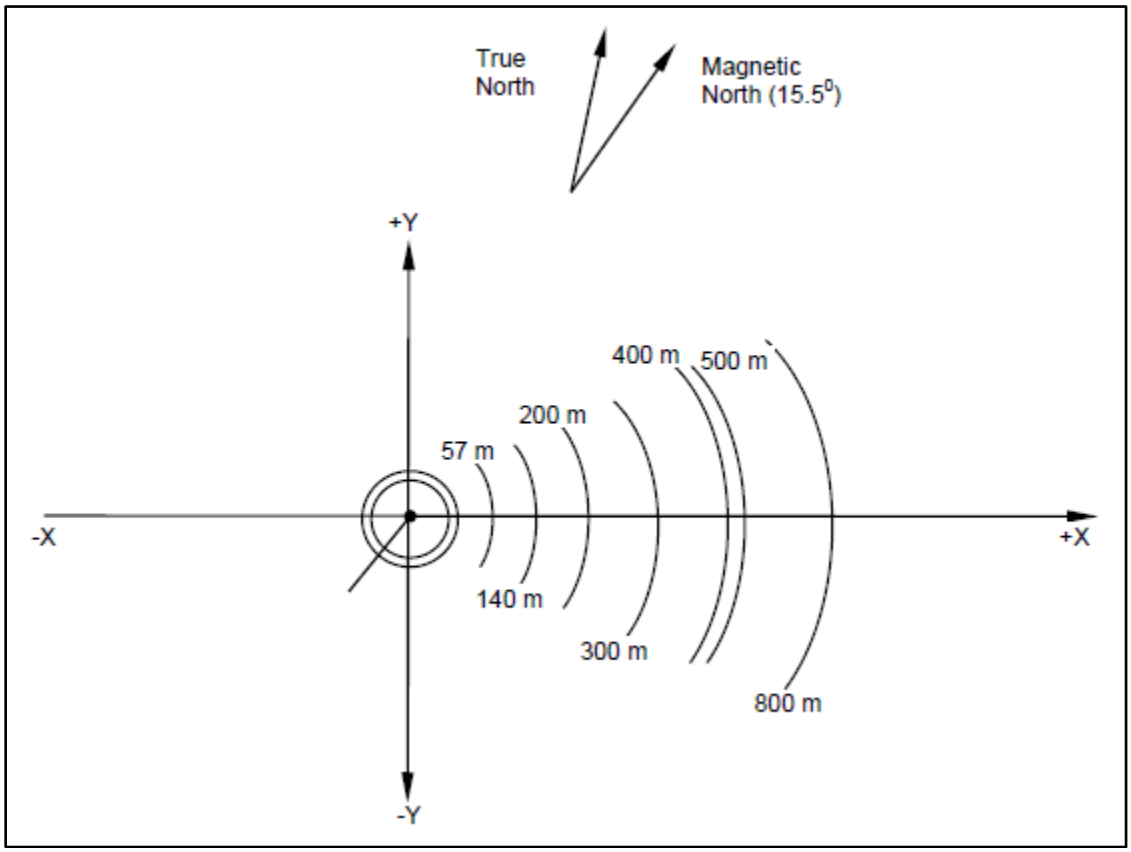

Figure 2-2. Burro spill area and measurement arcs [3].

2.2.2 Test Series Grouping and Rating

The Burro trials included in this MVD consisted of spills of LNG. The spill point is located in the center of a water test basin of approximately 58 m of diameter. The resulting clouds

[4] Previous model validation efforts by Hansen et al. [33] showed that the slight unevenness of the terrain had a noticeable effect on the lower wind speed trials (e.g., Burro 8). Therefore, CFD modelers may want to consider including the China Lake terrain in their simulations.

dispersed over open water and then over the terrain immediately downwind of the water test basin, with no obstructions. The test series therefore fits in the following categories:

- Material: LNG
- Release Type: Spill
- Dispersion Area: Unobstructed

Modeling vapor dispersion from LNG spills is a regulatory requirement in siting studies. Therefore, the Burro trials included in the MVD are highly relevant to the purpose of this MVD ("Relevance" rating = 5 and "Material" rating = 5). The release flow rates and the downwind distances over which the cloud dispersion was measured scale well with typical facility siting scenarios ("Scale" rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2).

The overall quality and availability of data from the Burro trials is considered acceptable for the purpose of this MVD ("Data quality/availability" rating = 3).

Overall, the Burro series is rated at 4.0, which is above the "acceptable" threshold; therefore, the Burro test series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the Burro series in the MVD for LNG spills [3].

2.2.3 Test Series Observations and Comments

Four of the Burro trials were included in the LNG spills database by Stewart et al. In order to balance the number of low-momentum and jet releases, only 3 of those trials are included in this MVD. Rapid phase transition (RPT) events occurred during Burro 9, which reportedly affected the concentration measurements at the 57 m arc; therefore, Burro 9 is not included in this MVD.

Table 2-6 lists the main test parameters for the trials included in the flammable dispersion MVD. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the LNG spills database by Stewart et al. Additional information on these trials can be found in the references listed in the summary table.

Table 2-6. Burro test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atm. Stability Class
BU 3	88.0	167	5.4 @ 3 m	C
BU 7	99.5	174	8.4 @ 3 m	D
BU 8	116.9	107	1.8 @ 3 m	E

The thermodynamic properties of LNG most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial, based on the mixture composition provided in the MVD. These should be used in models which do not have a species database, or which do not include the released material.

2.2.4 Time Averaging

The data included in the MDA database is reported at 1 Hz frequency. Therefore, the short time averaging for the Burro trials is considered as 1 s. As discussed in Section 1.9.2, the long averaging time is normally set to the duration of the steady portion of the release. The long averaging times defined in this MVD are consistent with those specified in the LNG spills database. Table 2-7lists the short and long averaging times for the Burro trials.

Table 2-7. Averaging times for the Burro trials.

Trial	Short time avg.	Long time avg.
BU 3	1 s	100 s
BU 7	1 s	140 s
BU 8	1 s	80 s

2.2.5 Test Series Sensitivities

The boundary conditions and source data for the base case, for each Burro trial in the MVD, are specified as in the model validation database by Stewart et al. [3]. The sensitivity cases are specified based on a review of the test series references and the DEGADIS model evaluation report by FERC [20]. Table 2-8 lists the parameters values for the base and sensitivity cases.

2.2.5.1 Source Term

The source sensitivity for the Burro trials was evaluated by FERC using three different approaches: a time-varying LNG pool source model and two different steady state pools with vaporization rates of 0.167 kg/m^2-s and 0.085 kg/m^2-s, respectively. For consistency, the same values are applied in this MVD. The time-varying pool model is taken as the base case, since most current dispersion models include this source term capability.

The spill rate and duration are taken from the test series report; no sensitivity to these values is required.

2.2.5.2 Wind Speed

FERC specified wind speed sensitivity cases for the Burro trials, due primarily to a slow drift in wind speed during each trial. The high and low cases were set, respectively, as the upper and lower quartiles of the wind speed data. The same sensitivity cases are specified in this MVD, for consistency with previous validation efforts. In all cases, the wind profile (speed and direction) should be kept steady throughout the simulation.

2.2.5.3 Atmospheric Stability

Sensitivity cases for atmospheric stability were specified for some of the Burro trials, where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class. The values specified in this MVD match those listed by FERC.

2.2.5.4 Roughness Length

For the Burro trials, Stewart et al. reported a roughness length of 0.0002 m, consistent with the MDA and most reports on these trials. FERC suggested a sensitivity case with a roughness length of 0.01 m, as “the upper range of soils and short grass”; an increase of nearly two orders of magnitude seems excessive, given the strong effect this parameter can have on atmospheric dispersion. Therefore, the upper bound for the roughness length in this MVD is set to 0.002 m (one order of magnitude higher than the base case).

2.2.5.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature are specified, given the small temperature fluctuations and measurement uncertainties.

The ambient pressure during the Burro trials was measured and reported lower than 1 atmosphere; therefore, the base case is set to the reported pressure and a sensitivity to

ambient pressure is specified (for models that allow the ambient pressure to be modified) by setting the ambient pressure to 1 atm.

FERC conducted sensitivity runs to relative humidity for some of the Burro trials. However, given the small difference in values (less than 8%) and the small effect observed on the results for the DEGADIS model, no sensitivity cases to relative humidity are included in this MVD for the Burro trials.

2.2.5.6 Material Properties

The Burro trials involved spills of LNG. Koopman et al. [29] provided the actual composition for the LNG mixture used in each trial, which is therefore used to define the base case. Given the common (and generally conservative) practice of modeling LNG releases as pure methane, a sensitivity case with 100% methane is included in the MVD.

2.2.5.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts for the Burro trials should include the sensitivity cases listed in Table 2-8. If one or more sensitivity cases cannot be run (for example, due to hard-coding of certain parameters in a model), an explanation should be provided in the model questionnaire.

Table 2-8. Base and sensitivity cases for the Burro trials in the MVD.

Parameter	Case	Burro 3	Burro 7	Burro 8
Source term	Base	Spreading pool	Spreading pool	Spreading pool
	S1	Steady pool, 0.167 kg/m²-s vap. rate	Steady pool, 0.167 kg/m²-s vap. rate	Steady pool, 0.167 kg/m²-s vap. rate
	S2	Steady pool, 0.085 kg/m²-s vap. rate	Steady pool, 0. 085 kg/m²-s vap. rate	Steady pool, 0.085 kg/m²-s vap. rate
Release Rate	Base	88.0 kg/s	99.5 kg/s	116.9 kg/s
Release Duration	Base	167 s	174 s	107 s
Wind Speed (at 3 m height)	Base	5.4 m/s	8.4 m/s	1.8 m/s
	W1	5.8 m/s	N/A	2 m/s
	W2	5.1 m/s	N/A	1.5 m/s
Surface Roughness Length	Base	0.0002 m	0.0002 m	0.0002 m
	R1	0.002 m	0.002 m	0.002 m
Atmospheric Stability	Base	C	D	E
	A1	-	C	F
Ambient Temperature	Base	34.6 °C	33.8 °C	32.9 °C
Ambient Pressure	Base	0.936 atm	0.928 atm	0.929 atm
	P1	1 atm	1 atm	1 atm
Relative Humidity	Base	5.2%	7.4%	4.5%
Stream Composition	Base	Methane = 92.5% Ethane = 6.2% Propane = 1.3%	Methane = 87.0% Ethane = 10.4% Propane = 2.6%	Methane = 87.4% Ethane = 10.3% Propane = 2.3%
	C1	Methane = 100%	Methane = 100%	Methane = 100%

2.3 Chemical Hazards Research Center (CHRC) Wind Tunnel

Experimental campaign	Chemical Hazards Research Center (CHRC)
Test dates:	N/A
Number of trials:	N/A
Test location:	Chemical Hazards Research Center (CHRC) at the University of Arkansas
Tests performed by:	CHRC
Brief description:	Carbon dioxide gas release in a wind tunnel. Dispersion includes cases with a dike and tank.
References:	Stewart et al., 2016 [3] Havens et al., 2007 [34]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Low-momentum
Dispersion Area:	Unobstructed; Complex geometry
Test series rating	
Overall:	**3.0**
Relevance:	4
Material:	2
Scale:	1
Repeatability:	4
Data Quality/Availability:	4

2.3.1 Description

The CHRC test series consisted of carbon dioxide (CO_2) gas releases in wind tunnels; they were conducted at the University of Arkansas' Chemical Hazards Research Center (CHRC) wind tunnel facility. The source term consisted of a ground-level release, resulting in a low-velocity vertical flow through the wind tunnel floor. Different configurations were tested, including unobstructed, with a dike around the release area, and with a tank in the middle of the release area. Figure 2-3 shows a picture of the CHRC wind tunnel configuration for a trial with tank and dike.

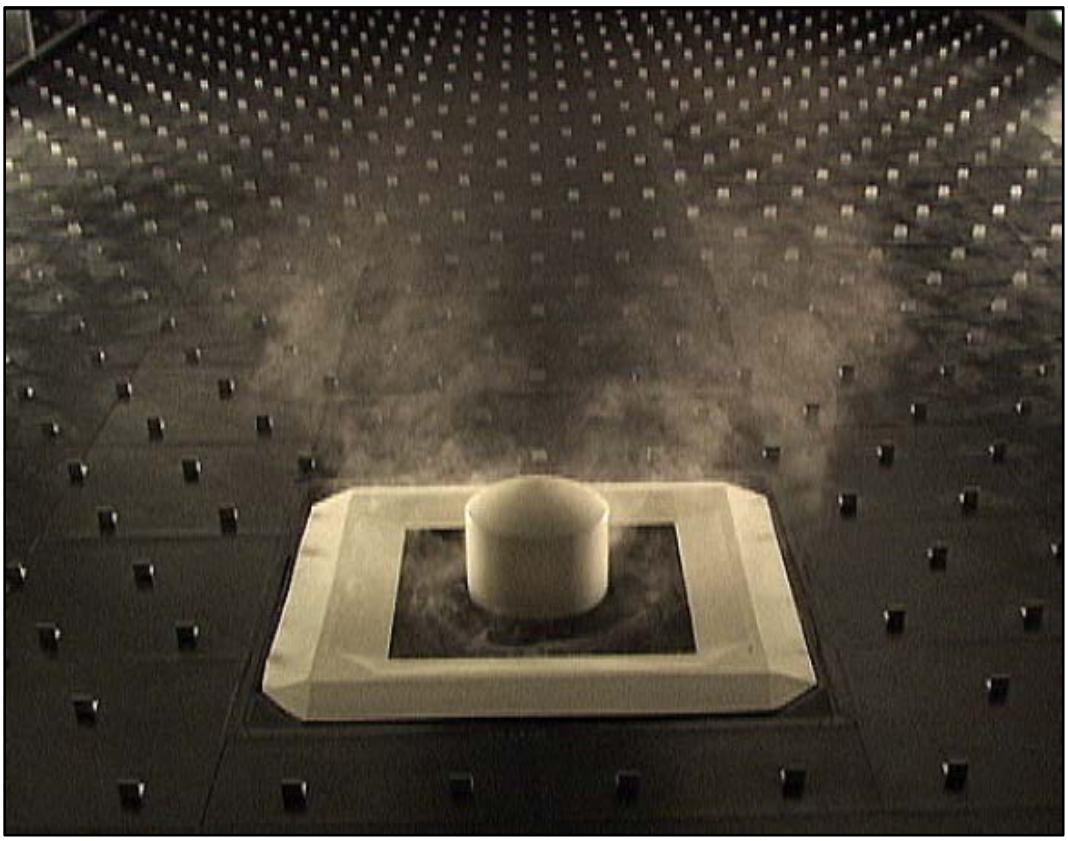

Figure 2-3. CHRC configuration for a trial with tank and dike [34].

The CHRC wind tunnel consisted of a working area measuring 24.4 m (80 ft) long, 6.1 m (20 ft) wide, and 2.2 m (7.5 ft) tall; flow was pushed through the test section by upwind fans. The experiments were set up for a scale of 1:150. CO_2 was introduced through a meshed screen over a square area (63 cm length and width) flush with the tunnel floor, with a central disk (31 cm diameter) blocked off; the total flow area measured 0.334 m^2. Some of the trials included a dike (3.7 cm tall) around the square source area, and a tank (28.3 cm tall) over the central blocked area.

2.3.2 Test Series Grouping and Rating

The CHRC trials included in this MVD consisted of low-momentum, continuous releases of CO_2 (with 1.5% propane as a tracer) through the floor of a wind tunnel. The resulting clouds were advected through the wind tunnel and dispersed over different configurations – both unobstructed and in a layout intended to scale the spill containment system for a single-containment LNG storage tank. The test series therefore fit in the following categories:

- Material: Non-flammable
- Release Type: Low-momentum
- Dispersion Area: Unobstructed; Complex geometry

The ground-level source term is representative of vapor generation form an evaporating liquid pool, and the presence of the tank and dike is intended to represent the LNG storage area in LNG facilities; therefore, the scenarios modeled in the CHRC trials are relevant for siting studies ("Relevance" rating = 4). Carbon dioxide is not a material used in LNG facilities; however, the use of CO_2 to produce dense clouds in wind tunnel trials is well established ("Material" rating = 2).

Wind tunnel tests are performed at a scale much smaller than actual plants. While this has benefits in terms of costs and controllability of boundary conditions, the reduced scale tends to increase the effect of near-wall phenomena on the overall behavior of the cloud, which in turn may affect the model's performance for reasons not relevant to its intended applications. Therefore, the scale of wind tunnel trials is considered a poor fit for this MVD ("Scale" rating = 1).

Wind tunnel trials allow the source term and boundary conditions to be finely controlled, allowing for steady state conditions to be achieved and sustained for long periods of time. Therefore, the repeatability of the experiments is more than acceptable ("Repeatability" rating = 4). The overall quality and availability of data is considered more than acceptable for the purpose of this MVD ("Data quality/availability" rating = 4).

Overall, the CHRC series is rated at 3.0, which meets the "acceptable" threshold; therefore, the test series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the CHRC series in the MVD for LNG spills [3].

2.3.3 Test Series Observations and Comments

The LNG spills database [3] included three CHRC trials; the same trials are included in the current MVD, to provide continuity for models previously evaluated against that database.

Table 2-9 lists the main test parameters for the trials included in the flammable dispersion MVD. The values provided in the table are at wind tunnel scale. Some models may be unable to perform simulations at these scales; therefore, for each wind tunnel trial, the accompanying spreadsheet also includes data at full scale. The wind tunnel scale remains the preferred option for models capable of simulating small scales.

Table 2-9. CHRC test parameters.

Test No.	Spill Rate [kg/s]	Wind Speed [m/s]	Obstructions
CHRC-A	0.011 kg/s	0.4 @ 67 mm	-
CHRC-B	0.011 kg/s	0.4 @ 67 mm	Dike and tank
CHRC-C	0.011 kg/s	0.4 @ 67 mm	Dike

The thermodynamic properties of CO_2 most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial. These should be used in models which do not have a species database, or which do not include the released material.

2.3.4 Time Averaging

The CHRC wind tunnel trials were run to steady state; therefore, the concept of averaging time is not as critical as in a transient scenario and, with the possible exception of the initial and final transients, short- and long-time averaging should provide the same results. Therefore, only long time averages are considered for the wind tunnel trials. The averaging times are listed in Table 2-10.

Table 2-10. Averaging times for the CHRC trials.

Trial	Long time avg.
CHRC-A	120 s
CHRC-B	120 s
CHRC-C	120 s

2.3.5 Test Series Sensitivity Cases

The CHRC wind tunnel tests were conducted under well controlled and steady atmospheric conditions, and with well-defined source terms. Therefore, no sensitivity cases relative to atmospheric conditions or source term are required for the CHRC trials.

Table 2-11 summarizes the source parameters and ambient conditions for the CHRC trials in the MVD. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the database developed by Stewart et al. Additional information on these trials can be found in the references listed in the summary table.

Table 2-11. Base cases for the CHRC trials in the MVD.

Parameter	Case	CHRC-A	CHRC-B	CHRC-C
Source term	Base	Low-momentum ground level injection	Low-momentum ground level injection	Low-momentum ground level injection
Release Rate	Base	0.011 kg/s	0.011 kg/s	0.011 kg/s
Release Duration	Base	Continuous	Continuous	Continuous
Wind Speed (at 0.067 m height)	Base	0.4 m/s	0.4 m/s	0.4 m/s
Surf. Roughness Length	Base	7.2E-4 m	7.2E-4 m	7.2E-4 m
Atmospheric Stability	Base	D	D	D
Ambient Temperature	Base	22.9 °C	22.9 °C	22.9 °C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	N/A	N/A	N/A
Stream Composition	Base	CO_2 = 98.5% Propane = 1.5%	CO_2 = 98.5% Propane = 1.5%	CO_2 = 98.5% Propane = 1.5%

2.4 Coyote

Experimental campaign	Coyote (CO)
Test dates:	1981
Test location:	China Lake, California
Number of tests:	9
Tests performed by:	Naval Weapons Center and Lawrence Livermore National Laboratory
Brief description:	LNG spills onto water; unobstructed vapor cloud dispersion over land.
References:	Stewart et al., 2016 [3] Ermak et al., 1989 [32] Goldwire et al., 1983 [35]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	LNG, liquid methane
Release Type:	Spill
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**4.0**
Relevance:	5
Material:	5
Scale:	5
Repeatability:	2
Data Quality/Availability:	3

2.4.1 Description

The Coyote test series was conducted at China Lake and included 7 spills of LNG and 2 spills of liquid methane, both on water. The vapor clouds produced by the evaporation of the liquid spills dispersed over mostly flat terrain; Figure 2-4 shows a schematic of the spill area and measurement arcs. Most of the sensors were placed between 140 and 400 m downwind of the spill location.

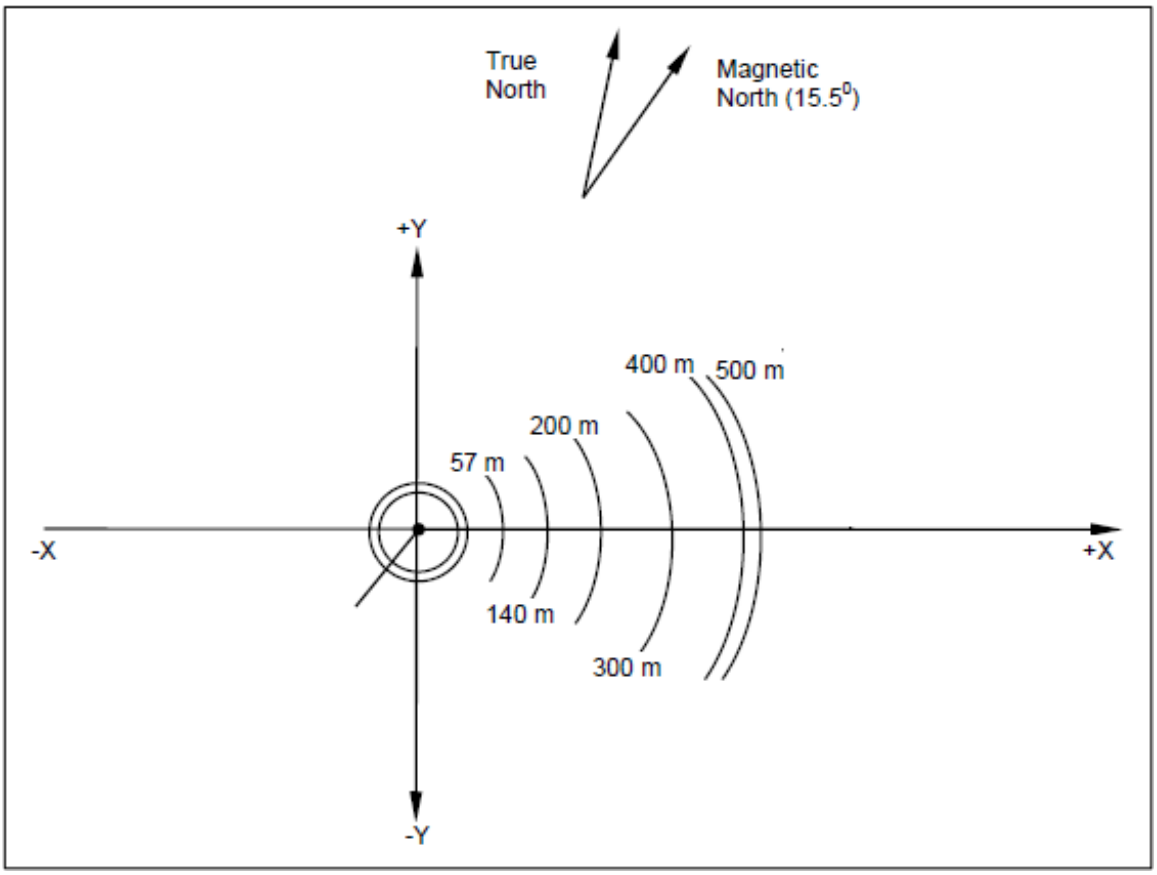

Figure 2-4. Coyote spill area and measurement arcs [3].

2.4.2 Test Series Grouping and Rating

The Coyote trials included in this MVD consisted of spills of LNG onto water. The spill point was located in the center of a water test basin of approximately 58 m of diameter. The resulting clouds dispersed over open water and then over the terrain immediately downwind of the water test basin, with no obstructions. The test series therefore fits in the following categories:

- Material: LNG
- Release Type: Spill
- Dispersion Area: Unobstructed

Modeling vapor dispersion from LNG spills is a regulatory requirement in siting studies. Therefore, the Coyote trials included in the MVD are highly relevant to the purpose of this MVD ("Relevance" rating = 5 and "Material" rating = 5).

The release flow rates and the downwind distances over which the cloud dispersion was measured scale well with typical facility siting scenarios ("Scale" rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2).

The overall quality and availability of data from the Coyote trials, for the purpose of this MVD is considered acceptable for the purpose of this MVD ("Data quality/availability" rating = 3).

Overall, the Coyote series is rated at 4.0, which is above the "acceptable" threshold; therefore, the Coyote test series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the Coyote series in the MVD for LNG spills [3].

2.4.3 Test Series Observations and Comments

The purpose of the Coyote test series was to observe the flame propagation after the flammable vapor cloud dispersing from the liquid pool was ignited. Therefore, for vapor dispersion modeling purposes, each Coyote trial ended at the time of ignition of the vapor cloud to ensure that the measured concentrations were not affected by the flame.

Three trials from the Coyote test series were included in the model validation database for LNG spills by Stewart et al. [3]; the same trials are included in the current MVD, to provide continuity for models previously evaluated against that database. Table 2-12 lists the main test parameters for these trials. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the MDA database and the LNG spills database. Additional information on these trials can be found in the references listed in the summary table.

Table 2-12. Coyote test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Ignition Time [s]	Wind Speed [m/s]	Atm. Stability Class
CO 3	100.7	65	99.7	6.0 @ 3 m	C
CO 5	129.0	98	132.7	9.7 @ 3 m	C
CO 6	123.0	82	108	4.6 @ 3 m	D

The thermodynamic properties of LNG most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial, based on the mixture composition provided in the MVD. These should be used in models which do not have a species database, or which do not include the released material.

2.4.4 Time Averaging

The data included in the MDA database is reported at 1 Hz frequency. Therefore, the short time averaging for the Coyote trials is considered as 1 s. The long time averaging is set to the duration of steady portion of the release, as specified by Stewart et al. The short and long averaging times are summarized in Table 2-13.

Table 2-13. Time averaging for the Coyote trials.

Trial	Short time avg.	Long time avg.
CO 3	1 s	50 s
CO 7	1 s	90 s
CO 8	1 s	70 s

2.4.5 Test Series Sensitivities

The boundary conditions and source data for the base case, for each Coyote trial in the MVD, are specified as in the model validation database. The sensitivity cases are specified based on a review of the test series references and the DEGADIS model evaluation report by FERC. Table 2-14 lists the parameter values for the base and sensitivity cases.

2.4.5.1 Source Term

The source sensitivity for the Coyote trials was evaluated by FERC using three different approaches: a time-varying LNG pool source model and two different steady state pools with vaporization rates of 0.167 kg/m^2-s and 0.085 kg/m^2-s, respectively. For consistency, the same values are applied in this MVD. The time-varying pool model is taken as the base case, since most current dispersion models include this source term capability.

The spill rate and duration are taken from the test series report; no sensitivity to these values is required.

2.4.5.2 Wind Speed

The wind speed data during the Coyote trials in the MVD did not present sufficient uncertainty or variability to warrant sensitivity analysis [20].

2.4.5.3 Atmospheric Stability

Sensitivity cases for atmospheric stability are specified for some of the Coyote trials, where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class. The sensitivity cases specified here match those listed by FERC.

2.4.5.4 Roughness Length

For the Coyote trials, Stewart et al. reported a roughness length of 0.0002 m, consistent with the MDA and most reports on these trials. FERC suggested a sensitivity case with a roughness length of 0.01 m, as “the upper range of soils and short grass”; an increase of nearly two orders of magnitude seems excessive, given the strong effect this parameter can have on atmospheric dispersion. Therefore, the upper bound for the roughness length in this MVD is set to 0.002 m (one order of magnitude higher than the base case).

2.4.5.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature are specified, given the small temperature fluctuations and measurement uncertainties.

The ambient pressure during the Coyote trials was measured and reported lower than 1 atmosphere, therefore the base case is set to the reported pressure and a sensitivity to ambient pressure is specified (for models that allow the ambient pressure to be modified) by setting the ambient pressure to 1 atm.

FERC conducted sensitivity runs to relative humidity for the Coyote trials [20]. Even though the low humidity levels are unlikely to significantly affect the cloud's behavior, the difference between the base case and the sensitivity case is greater than 10% in all trials, therefore the same sensitivity cases are included in this MVD.

2.4.5.6 Material Properties

The Coyote trials involved spills of LNG. Goldwire et al. [35] provided the actual composition for the LNG mixture used in each trial, which is therefore used to define the base case. Given the common (and generally conservative) practice of modeling LNG releases as pure methane, a sensitivity case with 100% methane is included in the MVD.

2.4.5.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-14. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-14. Base and sensitivity cases for the Coyote trials in the MVD.

Parameter	Case	CO 3	CO 5	CO 6
Source term	Base	Spreading pool	Spreading pool	Spreading pool
	S1	Steady pool 0.167 kg/m²-s vap. rate	Steady pool 0.167 kg/m²-s vap. rate	Steady pool 0.167 kg/m²-s vap. rate
	S2	Steady pool 0.085 kg/m²-s vap. rate	Steady pool 0. 085 kg/m²-s vap. rate	Steady pool 0.085 kg/m²-s vap. rate
Release Rate	Base	100.7 kg/s	129.0 kg/s	123.0 kg/s
Release Duration	Base	65 s	98 s	82 s
Wind Speed (at 3 m height)	Base	6.8 m/s	9.7 m/s	5.0 m/s
Surface Roughness Length	Base	0.0002 m	0.0002 m	0.0002 m
	R1	0.002 m	0.002 m	0.002 m
Atmospheric Stability	Base	C	C	D
	A1	N/A	D	E
Ambient Temperature	Base	38.3 °C	28.3 °C	24.1 °C
Ambient Pressure	Base	0.924 atm	0.927 atm	0.929 atm
	P1	1 atm	1 atm	1 atm
Relative Humidity	Base	11.3%	22.1%	22.8%
	H1	3.5%	7.2%	4.5%
Stream Composition	Base	Methane = 79.4% Ethane = 16.4% Propane = 4.2%	Methane = 74.9% Ethane = 20.5% Propane = 4.6%	Methane = 81.8% Ethane = 14.6% Propane = 3.6%
	C1	Methane = 100%	Methane = 100%	Methane = 100%

2.5 Desert Tortoise

Experimental campaign	Desert Tortoise (DT)
Test dates:	August-September 1983
Test location:	Frenchman Flat, DOE Nevada Test Site
Number of tests:	4
Tests performed by:	Lawrence Livermore National Laboratory
Brief description:	Pressurized and liquefied anhydrous ammonia was released from a tank as a jet directed horizontally downwind. The release was located 0.79 m above ground and the dense vapor cloud dispersed over unobstructed, flat terrain. Ammonia concentrations and temperatures were measured along arcs at distances 100 and 800 m downwind, at heights ranging from 1 to 8.5 m.
References:	Goldwire et al., 1985 [36] Ott, 1995 [22] Ermak et al., 1989 [32]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**3.6**
Relevance:	5
Material:	3
Scale:	5
Repeatability:	2
Data Quality/Availability:	3

2.5.1 Description

The Desert Tortoise (DT) test series consisted of 4 large-scale pressurized ammonia releases dispersing over flat, unobstructed terrain. Pressurized liquid ammonia was released at flow rates between approximately 81 and 133 kg/s from a nozzle pointed horizontally downwind at a height of 0.79 m above ground. The release duration varied between approximately 2 and 6 minutes. All trials occurred under fairly strong winds (wind speeds of 5-7 m/s, measured at 2 m above ground), warm and dry air (29-34°C temperature and 10-21% relative humidity). Ammonia concentration was measured at several locations and elevations along two arcs, respectively 100 m and 800 m downwind of the release.

2.5.2 Test Series Grouping and Rating

The Desert Tortoise test series involved the release of anhydrous ammonia, liquefied under pressure and discharged downwind through an orifice of approximately 3–4 in. diameter. The resulting cloud dispersed over flat and unobstructed terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable[5]
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed

Even though anhydrous ammonia is not a common fluid to be considered in LNG facility siting, the release of pressurized liquids through orifices up to 4 inches in diameter is a scenario that typically needs to be modeled in siting studies. Therefore, the DT series is considered highly relevant to the purpose of this MVD (“Relevance” rating = 5). Since the cloud is non-flammable (at the measurement stations) and not cryogenic (liquefied ammonia was stored at ambient temperature), the species released is only considered acceptable (“Material” rating = 3). The release flow rates and the downwind distances over which the cloud dispersion was measured are both well within the range of typical facility siting scenarios (“Scale” rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited (“Repeatability” rating = 2).

The main limitation of the DT series is the placement of gas concentration sensors in arcs at only two downwind locations, which makes it difficult to discern how a model trends in prediction. However, the instrumentation and collected data were reported to be of

[5] As discussed in Section 1.2.

good quality. Therefore, the overall quality and availability of data is considered acceptable ("Data quality/availability" rating = 3).

Overall, the DT series is rated at 3.6, which is above the "acceptable" threshold; therefore, the DT series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the DT series in earlier model evaluation databases and protocols [14], [22], [37] as well as in model developers' internal validation efforts [38], [39].

2.5.3 Ambient Conditions

The meteorological array for the DT trials included 11 stations distributed around the release area and a 20 m tall tower located 50 m upwind. The stations measured atmospheric conditions at 2 m above ground, including temperature, the wind field and turbulence. The boundary layer profiles for temperature and wind speed were obtained from the 20 m tower. The location of the meteorological array instruments is shown later in Figure 2-7. For each trial, the wind and temperature were defined by averaging the data from the weather stations over a three-minute period starting at time zero (i.e., when the valve open signal was given).

An average roughness length of 0.003 m was used in the boundary layer calculations. This value is within a factor of two of the roughness lengths calculated for each individual trial.

2.5.4 Discharge System

The pressurized ammonia release system consisted of two tanker trucks, connected to a 6-inch spill line with remotely operated spill valve, flow meter, temperature and pressure transducers. The spill line terminated with an orifice plate, pointing horizontally downwind at 0.79 m above ground level; the spill line was oriented about the most prevalent wind direction (225° from North). The diameter of the orifice was 3.19 inches for the first trial (DT 1) and was increased to 3.72 inches for the later trials. Each tanker was pressurized to approximately 200 psia and high-pressure nitrogen was used to maintain the ammonia liquid until reaching the orifice, and the release at an approximately constant rate. The diagram of the ammonia discharge system is shown in Figure 2-5, and an aerial photograph is shown in Figure 2-6.

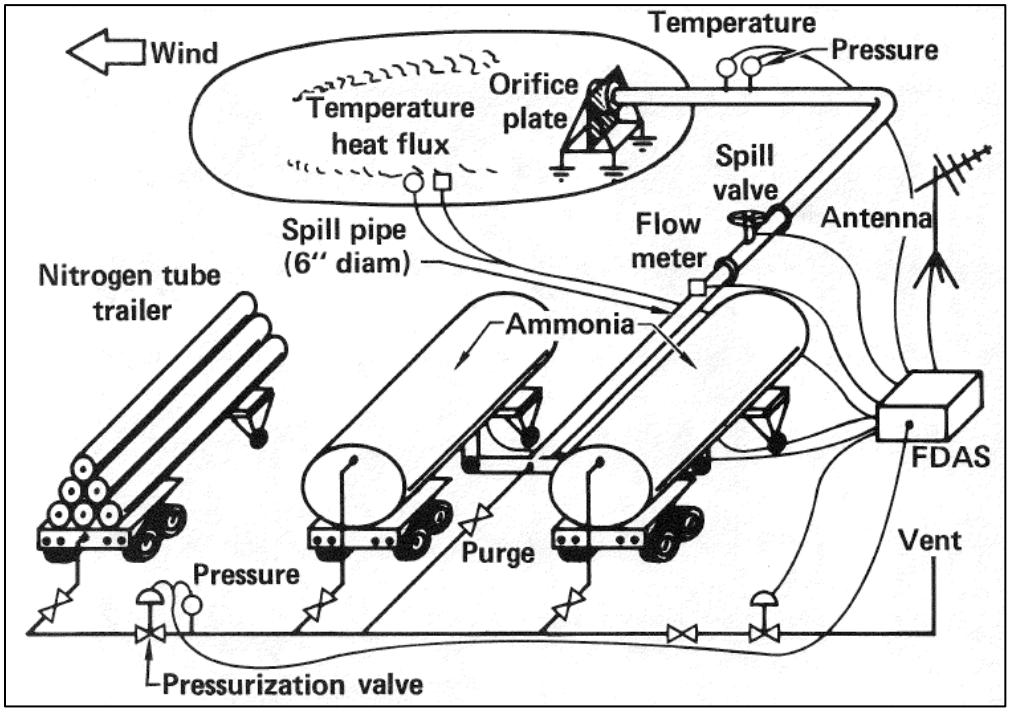

Figure 2-5. Schematic of the Desert Tortoise ammonia discharge system [36].

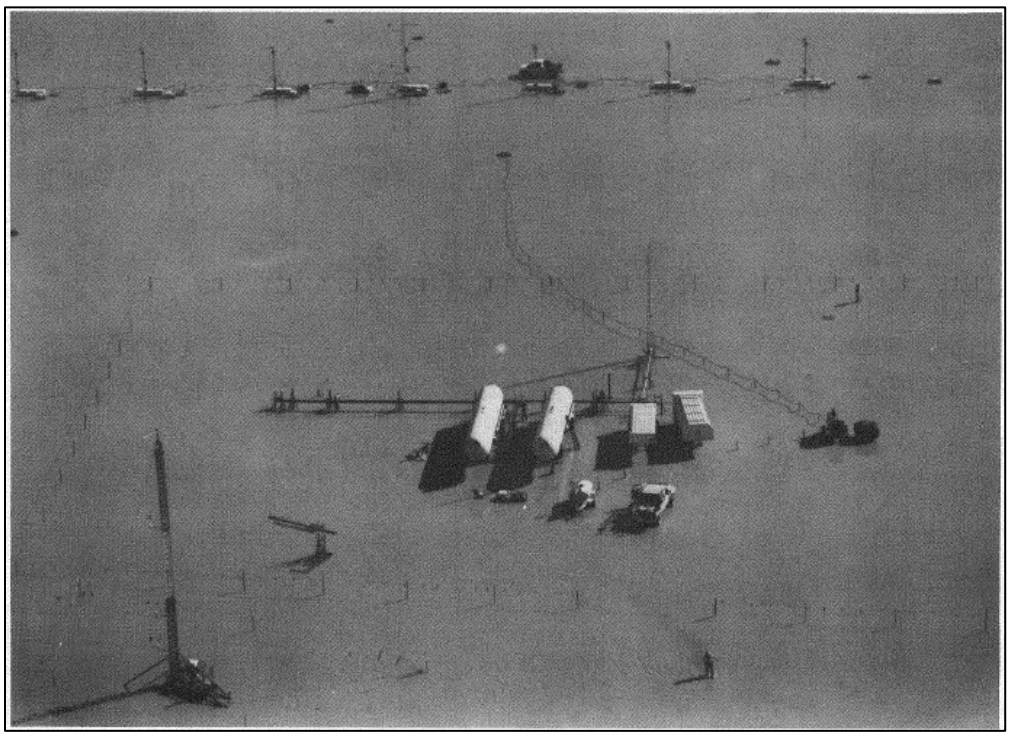

Figure 2-6. Aerial view of the Desert Tortoise ammonia release system [36].

The spill valve opened typically in 20-30 seconds and closed in about 10 seconds. All test data are referred to the valve open signal; however, due to the length of pipe between the spill valve and the orifice, the release of ammonia from the orifice began after approximately 20-30 seconds from the valve open signal.

The discharge system was designed to keep the ammonia liquid until it exited the orifice; upon discharge, the liquid ammonia would expand isentropically ("flash") to a mixture of liquid droplets (aerosol) and vapor. The flash fraction was calculated to be approximately 10 to 20%.

2.5.5 Instrumentation

The array of instrumentation for the measurement of the dispersing cloud consisted of two arcs with instrument stations distributed across the plume, respectively at 100 m and 800 m distance from the source, as shown in Figure 2-7. Each station included concentration and temperature sensors at three elevations, in order to gather information on the lateral spread of the cloud and its stratification.

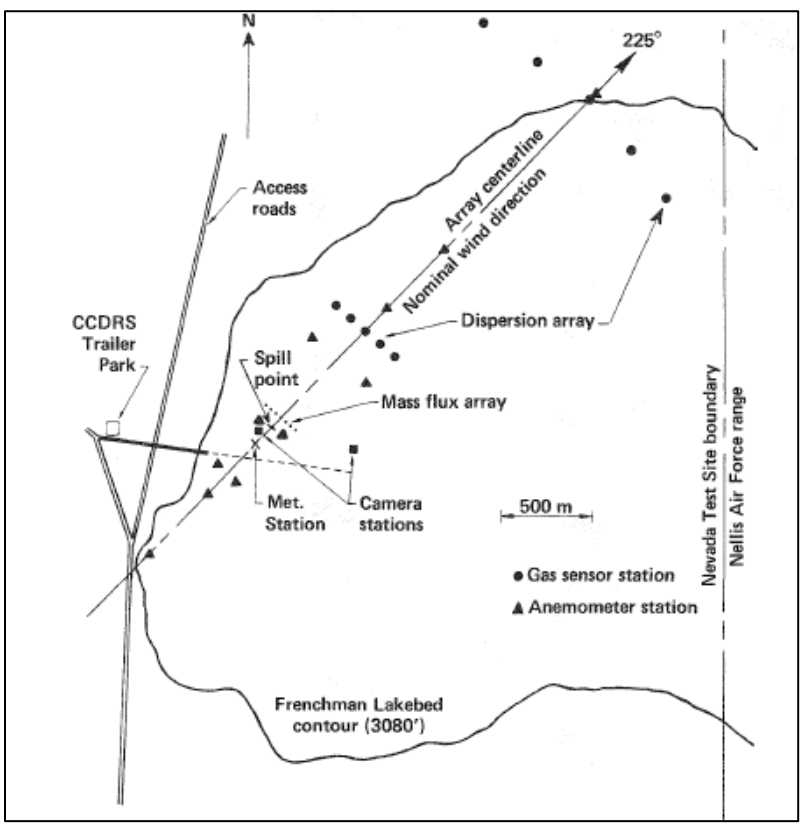

Figure 2-7. Map of the test area, including measurement towers [36].

The 100 m arc consisted of 7 stations with gas and temperature sensors at 1, 3.5, and 6 m height. The arc included one station along the array centerline and two sets of three

stations each on either side of the centerline, spaced 15.24 m apart. The gas concentration measurements were performed using infrared (IR) gas sensors and nondispersive infrared (NDIR) sensors. A comparison of the IR and NDIR measurements during the trials showed good agreement between the two types of instruments.

The 800 m arc consisted of 5 stations, each carrying three gas sensors and three thermocouples located at heights of 1, 3.5, and 8.5 m above the ground. The arc included one station along the centerline of the release system and two sets of two stations each on either side of the centerline, spaced 100 m apart. Solid state gas sensors could measure gas concentrations up to 3%, with an uncertainty of 20%; comparison with IR sensors showed very good agreement [36].

Additionally, portable ground-level stations were fielded at distances of 1,400 or 2,800 m (depending on the trial), and 5,500 m downwind. These stations used solid state sensors mounted 1 m above the ground and measured concentrations up to 5,000 ppm. Ammonia was detected at some of these stations, including 5.5 km downwind, in some of the trials; however, the data are not considered reliable for the purpose of model validation because of terrain effects (the terrain was not “flat” in this region), wind shifts, and the large distance between stations.

2.5.6 Experimental Uncertainty

The test series report by Goldwire et al. [36] includes limited information on the accuracy of the various instrumentation: the solid-state sensors are described as having an uncertainty of approximately 20% and being somewhat less accurate than the infrared sensors. Therefore, for the purpose of estimating uncertainty bands in the MVD, all gas concentration measurements in the DT series are therefore assumed to have 20% uncertainty.

2.5.7 Test Series Observations and Discussion

The DT test series consisted of four trials, all of which are included in this MVD. A summary of the test parameters is provided in Table 2-15. A more complete set of data for each test is included in the model validation spreadsheet.

Table 2-15. Desert Tortoise test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atmospheric Stability Class
DT-1	81.0	126	7.4 @ 2 m	D
DT-2	117.3	255	5.7 @ 2 m	D
DT-3	133.1	166	7.4 @ 2 m	D
DT-4	107.9	381	4.5 @ 2 m	E

The thermodynamic properties of ammonia most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial. These should be used in models which do not have a species database, or which do not include the released material.

2.5.8 Time Averaging

The Desert Tortoise data included in the REDIPHEM database, which is used in this MVD, consists of calibrated data at 1 Hz frequency. Therefore, the short time averaging for the Desert Tortoise trials is set to 1 second. The long time averaging is set to the duration of steady portion of the release, which varied for each trial. Table 2-16 summarizes the short and long time averaging values for the DT trials.

Table 2-16. Averaging times for the Desert Tortoise trials.

Trial	Short time avg.	Long time avg.
DT 1	1 s	100 s
DT 2	1 s	230 s
DT 3	1 s	140 s
DT 4	1 s	360 s

2.5.9 Test Series Sensitivities

Even though the DT trials were included in previous model evaluation efforts, no sensitivity cases were performed to evaluate the effect of uncertainty in the model input parameters. The following sensitivity cases are based on a review of available data.

2.5.9.1 Source Term

The DT source term consisted of a flashing liquid jet, whose pressure and temperature were measured throughout the discharge and found to be a relatively steady. Goldwire et al. reported some evidence of rainout following one of the trials. Given the lack of available data on the amount of rainout and the fact that several models may not allow for rainout to be calculated, the base case for the DT trials includes no rainout. A sensitivity case including liquid rainout is specified, to be performed if the model includes such capability.

The release rate was not measured directly, instead, an average release rate was calculated for each trial based on the total mass discharge and the duration of the release. The same approach was followed in several other test series. No sensitivity cases to release rate or duration are specified for the DT trials.

2.5.9.2 Wind Speed

No sensitivity cases are specified to wind speed.

2.5.9.3 Atmospheric Stability

Sensitivity cases for atmospheric stability are specified, for trials where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.5.9.4 Roughness Length

An average roughness length of 0.003 m was calculated by Goldwire et al. based on the meteorological data at the site; the calculated value was found to vary within approximately a factor of 4 across all trials. Given the effect of surface roughness on atmospheric dispersion, sensitivity cases are specified to span an order of magnitude around the average reported value.

2.5.9.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature, pressure or relative humidity are specified for the DT trials, given the small fluctuations and uncertainties in the data.

2.5.9.6 Material

The DT series consisted of releases of anhydrous ammonia. Models that include ammonia in their species database are expected to select that option; models that do not include ammonia in their database, or that require thermophysical properties to be specified by

the user, should use the values provided in the spreadsheet for each trial. No sensitivity cases to material properties are required.

2.5.9.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-17. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-17. Base and sensitivity cases for the Desert Tortoise trials in the MVD.

Parameter	Case	DT 1	DT 2	DT 3	DT 4
Source term	Base	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
	S1	Flashing jet, with rainout	Flashing jet, with rainout	Flashing jet, with rainout	Flashing jet, with rainout
Release Rate	Base	81.0 kg/s	117.3 kg/s	133.1 kg/s	107.9 kg/s
Release Duration	Base	126 s	255 s	166 s	381 s
Wind Speed (at 2 m height)	Base	7.4 m/s	5.8 m/s	7.4 m/s	4.5 m/s
Surface Roughness Length	Base	0.003 m	0.003 m	0.003 m	0.003 m
	R1	0.001 m	0.001 m	0.001 m	0.001 m
	R2	0.01 m	0.01 m	0.01 m	0.01 m
Atmospheric Stability	Base	D	D	D	E
	A1	C	-	C	D
Ambient Temperature	Base	29.3°C	30.5°C	33.5°C	33.0°C
Ambient Pressure	Base	0.91 atm	0.91 atm	0.91 atm	0.90 atm
	P1	1 atm	1 atm	1 atm	1 atm
Relative Humidity	Base	13%	17%	15%	21%
Stream Composition	Base	Ammonia = 100%	Ammonia = 100%	Ammonia = 100%	Ammonia = 100%

2.6 Eagle

Experimental campaign	Eagle Tests
Test dates:	September 17 – October 30, 1983
Test location:	Nevada Test Site
Number of tests:	6
Tests performed by:	Lawrence Livermore National Laboratory
Brief description:	Spills of liquid nitrogen tetroxide (N_2O_4) to evaluate source strength and vapor dispersion characteristics. Data was collected at 25 m and 785 m downwind.
References:	Ermak et al, 1989
Data confidentiality:	Included in REDIPHEM database
Model validation category	
Material:	Non-flammable
Release Phase:	Liquid
Release Type:	Spill
Dispersion Area:	Unobstructed (flat terrain)
Test series rating	
Overall:	**2.2**
Relevance:	3
Material:	2
Scale:	3
Repeatability:	2
Data Quality/Availability:	1

2.6.1 Description

The Eagle test series consisted of 6 liquid spills of nitrogen tetroxide (N_2O_4): four of the spills were used to evaluate vaporization and dispersion, while the other two spills were done to evaluate the performance of a Portable Foam Vapor Suppression System. The tests were conducted at the US Department of Energy (DOE) Nevada Test Site (NTS); the liquid N_2O_4 was spilled onto a dry lakebed. A single spill point was used to study evaporation rates as a function of pool depth and wind speed, and a multi-point spill was conducted to generate a large cloud for dispersion.

Data collected during the spill tests includes discharge temperature, heat flux from the soil, temperatures of the soil, liquid and vapor, and vapor concentration at downwind locations of 25 m and 785 m.

2.6.2 Test Series Grouping and Rating

The Eagle test series involved spills of liquid nitrogen tetroxide and dispersion over flat and unobstructed terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Spill
- Dispersion Area: Unobstructed

Vapor dispersion from liquid spills is considered in LNG facility siting studies, however, nitrogen tetroxide is not present at LNG facilities. The Eagle series is only considered somewhat relevant to the purpose of this MVD ("Relevance" rating = 3). Dispersion of oxidizers is not considered in LNG facility siting studies, therefore the species released is considered less than acceptable ("Material" rating = 2). The release flow rates are downscaled from typical LNG spill scenarios for facility siting, but the size of the test area is acceptable ("Scale" rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). Given the limited number of sensors available, the overall quality and availability of the data for the purpose of this MVD is considered poor ("Data quality/availability" rating = 1).

Overall, the Eagle test series is rated at 2.2, which is below the "acceptable" threshold. Given the availability of higher rated test series that fit the same categories, the Eagle trials are not included in the flammable dispersion MVD.

2.7 Falcon

Experimental campaign	Falcon (FAL)
Test dates:	1981
Test location:	Frenchman Flat, Nevada Test Site
Number of tests:	5
Tests performed by:	Lawrence Livermore National Laboratory
Brief description:	LNG spills onto water; obstructed vapor cloud dispersion.
References:	Stewart et al., 2016 [3] Brown et al., 1983 [40]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	LNG
Release Type:	Spill
Dispersion Area:	Obstructed
Test series rating	
Overall:	**4.0**
Relevance:	5
Material:	5
Scale:	5
Repeatability:	2
Data Quality/Availability:	3

2.7.1 Description

The Falcon test series included 5 trials performed at Frenchman Flat on the Nevada Test Site, which consisted of LNG spills on a water pond inside a fenced area. LNG was spilled at four locations onto a rectangular water basin measuring 40 m by 60 m. The goal of the Falcon tests was to evaluate the effectiveness of vapor barriers as a vapor dispersion mitigation technique; therefore, the spill pond was surrounded by vapor barriers: a 17.1 m long and 13.3 m tall barrier was placed upwind the water basin, and an 8.7 m tall vapor containment fence was placed all around the spill area, as shown in Figure 2-8. Figure 2-9 shows a schematic of the spill area and measurement rows.

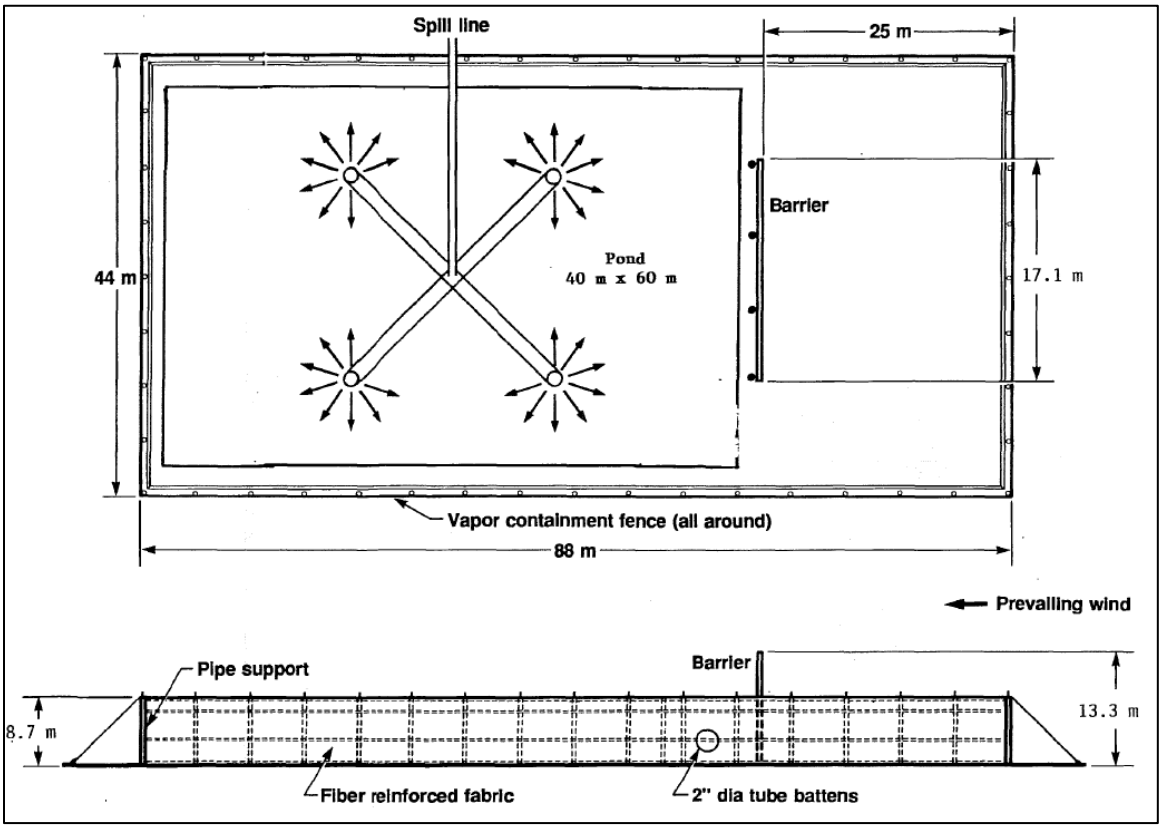

Figure 2-8. Falcon spill area and vapor barriers [1].

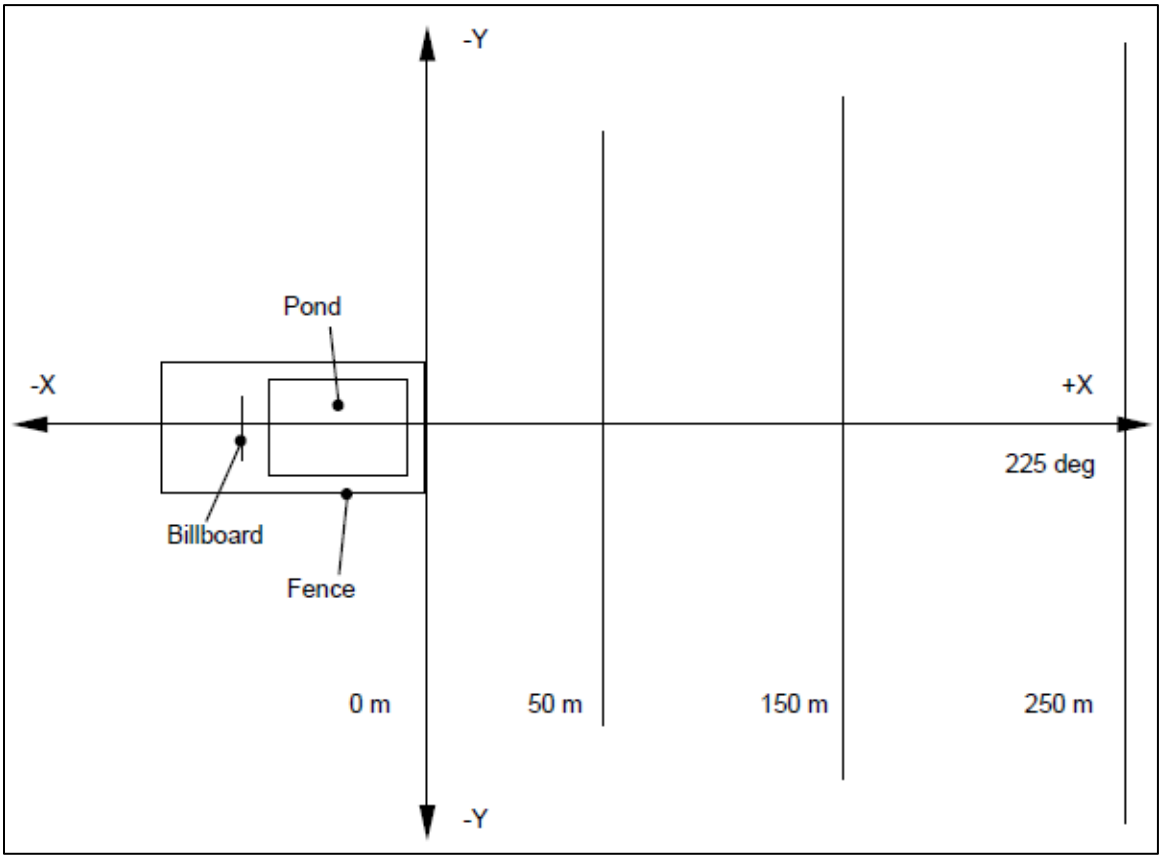

Figure 2-9. Falcon spill area and measurement arcs [3].

2.7.2 Test Series Grouping and Rating

The Falcon trials consisted of LNG spills onto a water surface. The resulting vapor clouds were obstructed by a vapor containment barrier, after which they could disperse over flat terrain. The test series therefore fits in the following categories:

- Material: LNG
- Release Type: Spill
- Dispersion Area: Obstructed

Modeling vapor dispersion from LNG spills is a regulatory requirement in siting studies. Therefore, the Falcon trials included in the MVD are highly relevant to the purpose of this MVD ("Relevance" rating = 5 and "Material" rating = 5). The release flow rates, the presence of vapor barriers and the downwind distances over which the cloud dispersion was measured scale well with typical facility siting scenarios ("Scale" rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). The overall quality and availability of data from the Falcon trials, for the purpose of this MVD is considered acceptable for the purpose of this MVD ("Data quality/availability" rating = 3).

Overall, the Falcon series is rated at 4.0, which is above the "acceptable" threshold; therefore, the Falcon test series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the Falcon series in the MVD for LNG spills [3].

2.7.3 Test Series Observations and Comments

Three trials from the Falcon test series were included in the LNG spills database; the same trials are included in the current MVD, to provide continuity for models previously evaluated against that database. Table 2-18 lists the main test. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the LNG spills database. Additional information on these trials can be found in the references listed in the summary table.

Table 2-18. Falcon test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atm. Stability Class
FAL 1	202.2	131	1.7	G
FAL 3	133.2	154	3.7	D
FAL 4	61.3	301	4.3	D-E

The thermodynamic properties of LNG most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial, based on the mixture composition provided in the MVD. These should be used in models which do not have a species database, or which do not include the released material.

2.7.4 Time Averaging

Both short and long time averaging for the Falcon trials are specified consistent with the source of data [3]. The values are summarized in Table 2-19.

Table 2-19. Averaging times for the Desert Tortoise trials.

Trial	Short time avg.	Long time avg.
FAL 1	1 s	100s
FAL 3	1 s	150 s
FAL 4	1 s	250 s

2.7.5 Test Series Sensitivities

The Falcon trials were included in previous model evaluation efforts. However, no sensitivity studies were performed to evaluate the effects of uncertainties in the model input parameters. The following sensitivity cases are based on a review of available data.

2.7.5.1 Source Term

The LNG delivery system in the Falcon trials was similar to other LNG releases performed around the same time, LNG was delivered through an above-ground pipe to the release location; a 90° bend in the pipe directed the LNG downward through an orifice; the resulting jet impinged vertically onto a spill plate that directed the flow radially on the water surface, as shown in Figure 2-10.

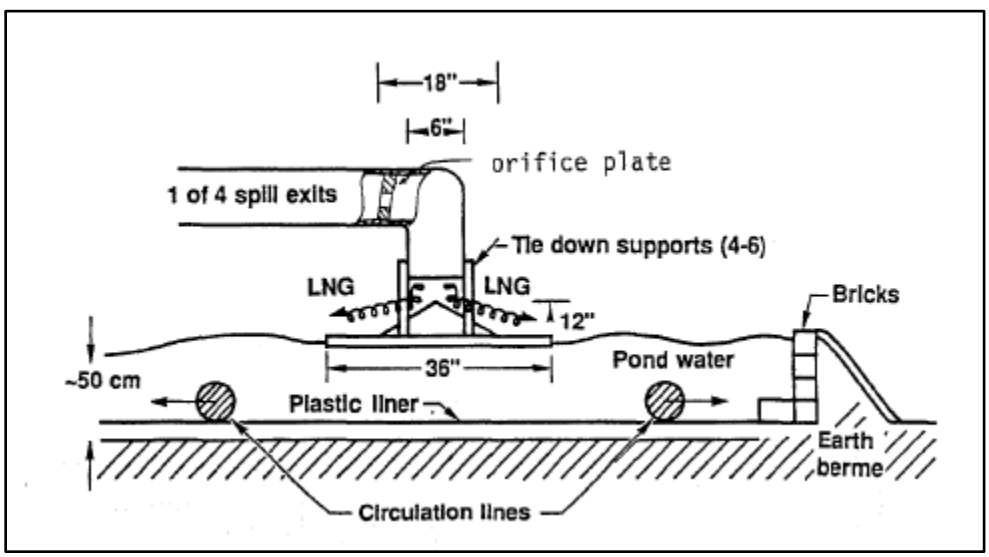

Figure 2-10 LNG spill system in the Falcon trials.

However, the behavior of the LNG source in the Falcon trials was different from the Burro, Coyote and Maplin Sands trials, and was difficult to replicate using the same evaporating pool source term models that are generally adequate for the other series. Gavelli et al. [41] utilized videos from the Falcon trials to observe and quantify the increased level of

turbulence above the LNG pool; the higher turbulence significantly improved the modeling results for the pool source model. Further improvements were also obtained by Hansen et al. [33], who modeled the Falcon releases as downward flashing jets with rainout, thus accounting for the momentum of the release.

Based on these modeling experiences, a sensitivity analysis to the source term characteristics is specified in this MVD: the spreading pool model, which is common to most current models, is considered the base case; the downward flashing jet is considered a sensitivity case; other source term properties (e.g., increased source turbulence or increased vaporization rate) can be specified based on each model's capabilities, as an additional recommended sensitivity case.

2.7.5.2 Wind Speed

No sensitivity cases are specified to wind speed.

2.7.5.3 Atmospheric Stability

Sensitivity cases for atmospheric stability are specified, for trials where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.7.5.4 Roughness Length

Stewart et al. reported a value of 0.008 m, based on the test series report by Brown et al. [40]; this is a significantly higher value than what is typically associated with smooth desert surfaces, therefore a sensitivity analysis to surface roughness is specified for the Falcon trials.

2.7.5.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature, pressure or relative humidity are specified for the Falcon trials, given the small fluctuations and uncertainties in the data.

2.7.5.6 Material Properties

Brown et al., 1983 [1] provided the methane/heavy split for the LNG mixture used in each trial, which is therefore used to define the base case. However, that information does not allow to define the actual mixture composition; therefore, the base case assumes 100% methane and no sensitivity cases are specified.

2.7.5.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-20. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-20. Base case and sensitivity cases for the Falcon test series.

Parameter	Case	FAL 1	FAL 3	FAL 4
Source term	Base	Spreading pool	Spreading pool	Spreading pool
	S1	Flashing jet, with rainout	Flashing jet, with rainout	Flashing jet, with rainout
	S2	Increased vaporization rate	Increased vaporization rate	Increased vaporization rate
Release Rate	Base	202.2 kg/s	133.2 kg/s	61.3 kg/s
Release Duration	Base	131 s	154 s	301 s
Wind Speed (at 2 m height)	Base	1.7 m/s	43.7 m/s	4.3 m/s
Surface Roughness Length	Base	0.008 m	0.008 m	0.008 m
	R1	0.001 m	0.001 m	0.001 m
Atmospheric Stability	Base	G	D	D
	A1	F	-	E
Ambient Temperature	Base	32.2°C	34.9°C	30.9
Ambient Pressure	Base	0.90 atm	0.89 atm	0.89 atm
	P1	1 atm	1 atm	1 atm
Relative Humidity	Base	N/A	4%	12%
Stream Composition	Base	Methane = 100%	Methane = 100%	Methane = 100%

2.8 FLADIS

Experimental campaign	FLADIS Field Experiments
Test dates:	April and August 1993, August 1994
Test location:	Hydro-Care training facilities, Landskrona, Sweden
Number of tests:	27
Tests performed by:	Risø National Laboratory
Brief description:	Dispersion of liquefied ammonia from small-orifice releases to study the near-source aerosol jet, the heavy gas dispersion phase, and the transition to passive dispersion. Downwind concentrations were measured along arcs at 20, 70 and 238 meters.
References:	Nielsen and Ott, 1996 [23] Nielsen, 1998 [42]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**2.6**
Relevance:	3
Material:	3
Scale:	3
Repeatability:	2
Data Quality/Availability:	2

2.8.1 Description

The FLADIS field experiments consisted of 27 small-scale ammonia releases dispersing over flat, unobstructed grassy terrain. Pressurized liquid ammonia was released at flow rates between approximately 0.2 and 0.6 kg/s from a nozzle pointed horizontally downwind with release durations up to 40 minutes. The nozzle diameter varied between 4 and 6.3 mm. Measurements of ammonia concentration were taken along three arcs at downwind distances of 20 m, 70 m, and 238 m.

2.8.2 Test Series Grouping and Rating

The FLADIS test series involved the release of liquid ammonia under pressure and discharged downwind through a small diameter nozzle. The resulting cloud dispersed over flat and unobstructed terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed

Ammonia is not a common fluid to be considered in LNG facility siting studies and the diameter of the orifice is much smaller than typically modeled in a siting study, however, flashing jet scenarios are required to be evaluated ("Relevance" rating = 3). Since the cloud is non-flammable (at the measurement stations) and not cryogenic (liquefied ammonia was stored at ambient temperature), the species released can only be considered acceptable ("Material" rating = 3). The release flow rates are significantly smaller than typical siting scenarios yet the measurement distances are quite long, resulting in very low measured concentrations ("Scale" rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). The FLADIS tests included arcs wider than the plume width at their respective downwind distances, however, sensors were only provided at one elevation in the second and third arcs. The test also used multiple gas detection methods. The overall quality and availability of the data, for the purpose of this MVD is considered less than acceptable ("Data quality/availability" rating = 2).

Overall, the FLADIS test series is rated at 2.6, which is below the "acceptable" threshold. Given the availability of higher rated test series that fit the same categories, the FLADIS trials are not included in the flammable dispersion MVD.

2.9 Flashing Liquids in Industrial Environment (FLIE)

Experimental campaign	Flashing Liquids in Industrial Environment (FLIE)
Test dates:	2004
Test location:	INERIS test site
Number of tests:	94
Tests performed by:	INERIS and von Karman Institute
Brief description:	Pressurized releases of propane or butane from a horizontal nozzle between 0.4 in and 2 in diameter. The main purpose of this project was to get a better understanding of the behavior of a two-phase discharge in the presence or in the absence of an obstacle.
References:	Bonnet and Lacome, 2014 [43] Lacome et al., 2020 [44] Bonnet, 2005 [45]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed; Obstructed
Test series rating	
Overall:	**Not suitable**
Relevance:	0
Material:	
Scale:	
Repeatability:	
Measurement Quality:	
Data Availability:	

2.9.1 Description

The Flashing Liquids in Industrial Environment (FLIE) test series consists of 94 pressurized releases of propane or butane from a horizontal nozzle between 0.4 in and 2 in diameter. The main purpose of this project was to develop models for calculating the interaction between a two-phase jet and an obstacle and to get a better understanding of the mechanisms steering the dispersion of a two-phase discharge in the presence or in the absence of an obstacle [45]. Therefore, while some of the trials allowed the flashing jet to travel unimpeded, most of the trials included a barrier at a distance between 0.8 and 2.6 m downwind, for the purpose of collecting liquid droplets and measuring liquid rainout. All measurements were performed with less than 10 m from the discharge location, as the focus of the trials was to characterize the two-phase region of the jet.

2.9.2 Test Series Grouping and Rating

The FLIE test series involved the release of propane or butane from a horizontal nozzle between 0.4 in and 2 in diameter. Some of the trials allowed the flashing jet to travel unimpeded, while other trials placed a barrier at a distance between 0.8 and 2.6 m downwind. The test series therefore fits in the following categories:

- Material: Flammable (non-LNG)
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed; Obstructed

The purpose of the FLIE trials was to examine the flashing jet behavior in proximity of the release (within approximately 10 m downwind), including quantifying the amount of rainout on the ground. While flashing jets represent a large number of facility siting scenarios, the purpose of the flammable dispersion MVD is to evaluate the far-field dispersion capabilities of a model. Therefore, the FLIE series is considered not relevant to the purpose of this MVD (“Relevance” rating = 0).

The FLIE series is thus not suitable for inclusion in the flammable dispersion MVD. The FLIE series will be reevaluated for possible inclusion in the source term MVD.

2.10 Goldfish

Experimental campaign	Goldfish (GF)
Test dates:	Summer 1986
Test location:	Frenchman Flat
Number of tests:	6
Tests performed by:	Lawrence Livermore National Laboratory
Brief description:	Pressurized and liquefied hydrofluoric acid was released as a jet from a tank through a 4-inch orifice directed horizontally downwind. The release was located 1 m above ground and the dense vapor cloud dispersed over unobstructed, flat terrain. Gas concentrations were measured along arcs at distances 300, 1000 and 3000 m downwind.
References:	Blewitt et al., 1987 [46] Hanna et al., 1991 [14] Zapert et al., 1991 [37]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**2.6**
Relevance:	5
Material:	2
Scale:	2
Repeatability:	2
Data Quality/Availability:	2

2.10.1 Description

The Goldfish (GF) test series consisted of 6 large-scale pressurized hydrofluoric acid (HF) releases dispersing over flat, unobstructed terrain. Pressurized liquid HF was released from a 4-inch nozzle pointed horizontally downwind at a height of 1 m above ground. All trials occurred under fairly strong winds (wind speeds of 4-7 m/s, measured at 2 m above ground), warm and dry air (21-37°C temperature and less than 20% relative humidity). The tests included a meteorological array and measurements of HF concentration at several locations along three arcs, respectively 300, 1000 and 3000 m downwind of the release. At each location, HF concentrations were measured at 1, 3 and 8 m above ground. The last three trials included water sprays, to evaluate their effectiveness for HF cloud volume control.

2.10.2 Test Series Grouping and Rating

The Goldfish test series involved the release of hydrogen fluoride, liquefied under pressure and discharged downwind through an orifice of 4-inch diameter. The resulting cloud dispersed over flat and unobstructed terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed

The release of pressurized liquid through orifices of 2-4 inch diameter is a very frequent scenario for facility siting (“Relevance” rating = 5). However, HF is not a material found in LNG facilities; additionally, HF presents peculiar thermodynamic properties that are not representative of other fluids found in LNG facilities (“Material” rating = 2). The cloud dispersion was measured at large distances from the source, resulting in gas concentrations well below the typical flammable range (“Scale” rating = 2).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited (“Repeatability” rating = 2). Limited information is available on the instrumentation and quality of the data recorded during the GF trials. Additionally, the gas concentration sensors were placed at only three downwind locations, fairly distant from each other. The MDA database includes data for each measurement sensor, but only at discrete times and for long time averages (66.6 s). The overall quality and availability of the data, for the purpose of this MVD is considered less than acceptable (“Data quality/availability” rating = 2).

Overall, the GF series is rated at 2.6, which is below the “acceptable” threshold; therefore, the Goldfish trials are not included in this MVD.

2.11 HSL-LPG

Experimental campaign	HSL-LPG
Test dates:	N/A
Test location:	Buxton, United Kingdom
Number of tests:	10
Tests performed by:	Health and Safety Laboratory
Brief description:	Horizontal pressurized jet releases of LPG through a 2-inch orifice, dispersing over flat terrain; 6 trials were unobstructed, while 4 included a barrier normal to the jet flow. Gas concentration and temperature measurements were recorded, prior to the vapor cloud being ignited.
References:	Butler and Royle, 2001 [47]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Flammable (non-LNG)
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed; Obstructed
Test series rating	
Overall:	**Not Suitable**
Relevance:	5
Material:	5
Scale:	3
Repeatability:	2
Data Quality/Availability:	**0**

2.11.1 Description

The Health and Safety Laboratory (HSL) conducted a series of experiments involving the horizontal release of liquefied petroleum gas (LPG) as part of a joint industry project. A total of 10 trials, with release rates up to 4.9 kg/s through a 2-inch (50 mm) orifice, were performed to investigate the ignition of vapor clouds formed by these releases; however, gas concentration and temperature measurements were performed prior to the ignition, which could be used to test dispersion models. Six of the trials comprised unobstructed release, while the other 4 included a solid barrier perpendicular to the jet flow.

A report by Butler and Royle [47] represents the only available reference for these trials; the HSL was contacted for additional information or data but none was received beyond what is included in the report.

2.11.2 Test Series Grouping and Rating

The HSL-LPG test series involved the release of propane, liquefied under pressure and discharged downwind through an orifice of approximately 2-inch diameter. The resulting cloud dispersed over slightly sloped terrain; in some trials, a 1-m tall barrier was placed approximately 15 m from the release to obstruct the cloud dispersion. The test series therefore fits in the following categories:

- Material: Flammable (non-LNG)
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed; Obstructed

The release of pressurized liquids through 2-4" diameter orifices, with dispersion affected by obstructions (e.g., vapor barriers) is a very common scenario for siting studies ("Relevance" rating = 5). Propane is used as a refrigerant (pure or mixed with other hydrocarbons) in virtually every LNG liquefaction facility, therefore, dispersion of propane releases is a frequent scenario in siting studies ("Material" rating = 5). The release flow rates (no more than 3 kg/s) and the downwind distances over which the cloud dispersion was measured (up to approximately 80 m) are somewhat small for the range of typical facility siting scenarios ("Scale" rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2).

Limited information is available on the instrumentation and quality of the data recorded during the HSL-LPG trials. The only available data on the propane cloud dispersion is represented by plots included in the report, which are limited to sample time traces for one trial, and concentration vs. distance plots based on long time averaged

measurements at one instance per trial. The HSL was contacted but was unable to provide additional data. The data is therefore considered not suitable for the purposes of the MVD ("Data quality/availability" rating = 0). The HSL-LPG trials are therefore considered not suitable for inclusion in the flammable dispersion MVD.

2.12 INERIS Ammonia Releases

Experimental campaign	INERIS (IN)
Test dates:	December 1996 – April 1997
Test location:	Centre of Scientific and Technical Studies of Aquitaine Outdoor Testing Site, near Bordeaux, France
Number of tests:	15
Tests performed by:	INERIS
Brief description:	Pressurized ammonia releases at flow rates of 2-4 kg/s, under different configurations: unobstructed; obstructed by impingement on a wall placed in proximity of the discharge; obstructed by impingement on the ground. Cloud dispersion occurred over flat terrain.
References:	Bouet, 2005 [48] Bouet et al., 2005 [49]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed; Obstructed
Test series rating	
Overall:	**2.8**
Relevance:	5
Material:	3
Scale:	3
Repeatability:	2
Data Quality/Availability:	1

2.12.1 Description

The INERIS ammonia dispersion test series (IN) consisted of 15 releases of pressurized liquid ammonia. The test series aimed at characterizing the source term, including the potential for rainout; therefore, three different configurations were tested [48]:

1. Unobstructed jet;
2. Jet impinging on a wall close to the source (less than 3 m downwind);
3. Jet impinging on the ground.

The flashing jet of ammonia was released from a storage vessel through a 2-in pipe and 2-in diameter orifice; for some of the trials, other orifices sizes and shapes (e.g., flange gap) were used. The release flow rates were set to 2-4 kg/s in order to fall between the Desert Tortoise (approximately 100 kg/s) and the FLADIS (approximately 0.5 kg/s) test series. The terrain on the test site was flat and free of obstacles, with the exception of the wall placed near the release location in some of the trials.

2.12.2 Test Series Grouping and Rating

The INERIS (IN) test series involved the pressurized release of liquefied anhydrous ammonia through a 2-inch diameter orifice. Different configurations were used, including horizontal and downward releases, free and impinging jets, and water curtains. The cloud then dispersed over flat and unobstructed terrain for up to 2 km. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed; Obstructed

Even though anhydrous ammonia is not a common fluid to be considered in LNG facility siting, the release of pressurized liquids through 2-in diameter orifices is a scenario that frequently needs to be modeled in siting studies (“Relevance” rating = 5). Since the cloud is non-flammable (at the measurement stations) and not cryogenic (liquefied ammonia was stored at ambient temperature), the species released is only considered acceptable (“Material” rating = 3). The release flow rates are smaller than typically encountered in facility siting scenarios (“Scale” rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited (“Repeatability” rating = 2). The major negative of the INERIS test series is the availability of data. In fact, no information is presented by Bouet on the discharge system besides the total released mass and release duration, even though pressure and temperature were measured at several locations within the storage vessel and all the

way to the orifice. Therefore, the source term for these trials is highly uncertain. Similarly, none of the time traces from the numerous sensors are available; instead, only long time averaged peak values are provided. Therefore, the overall quality and availability of the data, for the purpose of this MVD is considered poor ("Data quality/availability" rating = 1).

Overall, the INERIS series is rated at 2.8, which is below the "acceptable" threshold. Given the availability of higher-rated test series that fit the same categories, the INERIS series is not included in the flammable dispersion MVD.

2.13 Jack Rabbit Phase I

Experimental campaign	Jack Rabbit 1 (JRI)
Test dates:	April-May 2010
Test location:	Dugway Proving Ground, Utah
Number of tests:	10
Tests performed by:	West Desert Test Center
Brief description:	Pressurized and liquefied ammonia or chlorine releases through a 3 or 4-inch orifice directed downward from a 2 m elevation. The dense vapor cloud dispersed over unobstructed, flat terrain. Gas concentrations were measured along arcs at distances up to 2,500 m downwind.
References:	Fox and Storwold, 2011 [25] Storwold et al., 2011 [26] Hanna et al., 2012 [50]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**3.0**
Relevance:	2
Material:	2
Scale:	5
Repeatability:	2
Data Quality/Availability:	4

2.13.1 Description

The Jack Rabbit I (JRI) test series consisted of 10 large-scale releases of pressurized liquids (either anhydrous ammonia or chlorine) from the bottom of a storage tank, directed down to impinge on the ground at the center of a man-made depression (2 m deep and 50 m diameter); the resulting vapor cloud was then allowed to be dispersed by the wind over flat, unobstructed terrain. The test series consisted of 2 pilot trials (one with ammonia and one with chlorine) and 8 record trials (4 with ammonia and 4 with chlorine). The Jack Rabbit test program was conducted by West Desert Test Center (WDTC) at Dugway Proving Ground (DPG), Utah in April/May 2010.

The pressurized liquids were released through nozzles of 3 to 4 in diameter, with flow rates on the order of 50-70 kg/s. All trials were performed by design under low winds (wind speeds of 1-3 m/s). Measurements of gas concentration were performed at several locations and elevations along 8 arcs, ranging from 50 m to 2,500 m downwind of the release.

2.13.2 Test Series Grouping and Rating

The Jack Rabbit I test series involved the release of anhydrous ammonia or chlorine, liquefied under pressure and discharged vertically towards the ground. The resulting cloud dispersed over flat and unobstructed terrain, outside of a man-made depression centered around the release location. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed

The release of pressurized liquids through orifices up to 4 inches in diameter is a scenario frequently encountered in siting studies; however, downward releases are rarely required as they are frequently bounded by horizontal releases; the man-made depression surrounding the release further separates the JRI layout from scenarios of interest (“Relevance” rating = 2). Anhydrous ammonia and chlorine are not common fluids to be considered in LNG facility siting. Additionally, the cloud is non-flammable and not cryogenic (“Material” rating = 2). The release flow rates and the downwind distances over which the cloud dispersion was measured are within the range of typical facility siting scenarios (“Scale” rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited (“Repeatability” rating = 2). The measurement data is of high quality and was subjected to rigorous quality control and analysis. However, data access is only possible

via request to the Department of Homeland Security ("Data quality/availability" rating = 4).

Overall, the JRI series is rated at 3.0, which meets the "acceptable" threshold; given the availability of other flashing jet releases with more relevant configuration, the JRI series is not included in the flammable dispersion MVD.

2.14 Jack Rabbit Phase II

Experimental campaign	Jack Rabbit Phase 2 (JRII)
Test dates:	August 2015 – September 2016
Test location:	Dugway Proving Ground, Utah
Number of tests:	9
Tests performed by:	West Desert Test Center
Brief description:	Pressurized chlorine jet releases, between 5 and 20 tons per trial, from a 6-inch diameter hole. Tested different release directions (vertical up, vertical down and 45-degrees down) and dispersion through simulated urban area.
References:	Nicholson et al., 2015 [51] Byrnes and Mathew, 2016 [28] Nicholson et al., 2017 [27] Signature Science, 2015 [52]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Flashing Jet
Dispersion Area:	Complex terrain
Test series rating	
Overall:	**3.4**
Relevance:	4
Material:	2
Scale:	5
Repeatability:	2
Data Quality/Availability:	4

2.14.1 Description

The scope of the Jack Rabbit Phase 2 (JRII) trials was to expand upon the JRI results by performing chlorine releases on a larger scale. The JRII test series consisted of two phases: the first phase, conducted in 2015, included a simulated urban area through which the cloud would disperse; the urban-like obstructions were removed almost entirely for the second phase, conducted in 2016. A total of nine trials were performed during JRII: five during phase 1 and four during phase 2.

Pressurized liquid chlorine was released through 6-inch diameter nozzles at different orientations (most of the releases were pointed down towards the ground, but one trial each tested a vertical upward release and one pointed 45-degrees down from horizontal). Total released amounts ranged from 5 to 19.5 tons of chlorine. All trials occurred under low to moderate winds (wind speeds of 2 to 4 m/s) and temperate air. The tests included numerous instruments to record meteorological conditions around the dissemination area, and chlorine concentration at several locations within the urban-like grid and along several arcs up to 11 km downwind of the release.

2.14.2 Test Series Grouping and Rating

The Jack Rabbit II test series involved the release of large quantities of chlorine, liquefied under pressure and discharged downwind through a 6-inch diameter orifice. The resulting cloud dispersed through a simulated urban area and then flat and unobstructed terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Complex terrain

The release of large quantities of a pressurized liquid is a scenario that typically needs to be modeled in every siting study; however, the direction of the release directions (up, down, and angled down) are not common in siting scenarios. On the other hand, the presence of multiple obstructions downwind of the release is unique among flashing jet release experiments and useful for model validation (“Relevance” rating = 4). Chlorine is not a fluid to be considered in LNG facility siting; additionally, the cloud is non-flammable and not cryogenic (“Material” rating = 2). The release flow rates and the range of distances over which the cloud dispersion was measured (numerous measurements within the urban-like area and several arcs downwind) are both consistent with typical facility siting scenarios (“Scale” rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited (“Repeatability” rating = 2). The measurement data is of high quality and was

subjected to rigorous quality control and analysis. Only peak concentration values were obtained from the project repository[6]; however, additional data including time traces should be available to interested parties ("Data quality/availability" rating = 4).

Overall, the JRII series is rated at 3.4, which is above the "acceptable" threshold; therefore, the JRII series is considered suitable for inclusion in the flammable dispersion MVD.

2.14.3 Ambient Conditions

The meteorological array for the JRII trials included 49 portable weather instrumentation data systems (PWIDS), each including a propeller-vane wind monitor, temperature/humidity sensor, and data logger. With the exception of tower-mounted units, the PWIDS recorded ambient conditions at 2 m above ground; the sampling rate was 1 Hz, and the data was averaged over 10 seconds intervals. Three towers were deployed, each carrying PWIDS at 2, 4, 8, 16 and 32 m above ground. The location of the meteorological instrumentation is shown in Figure 2-11.

Ambient data were collected before, during, and after the dissemination. The reported values for each trial represent the mean of all the tripod PWIDS data recorded from the start of the dissemination until 60 minutes after [27].

[6] https://www.uvu.edu/es/jack-rabbit/, last accessed on June 16, 2020.

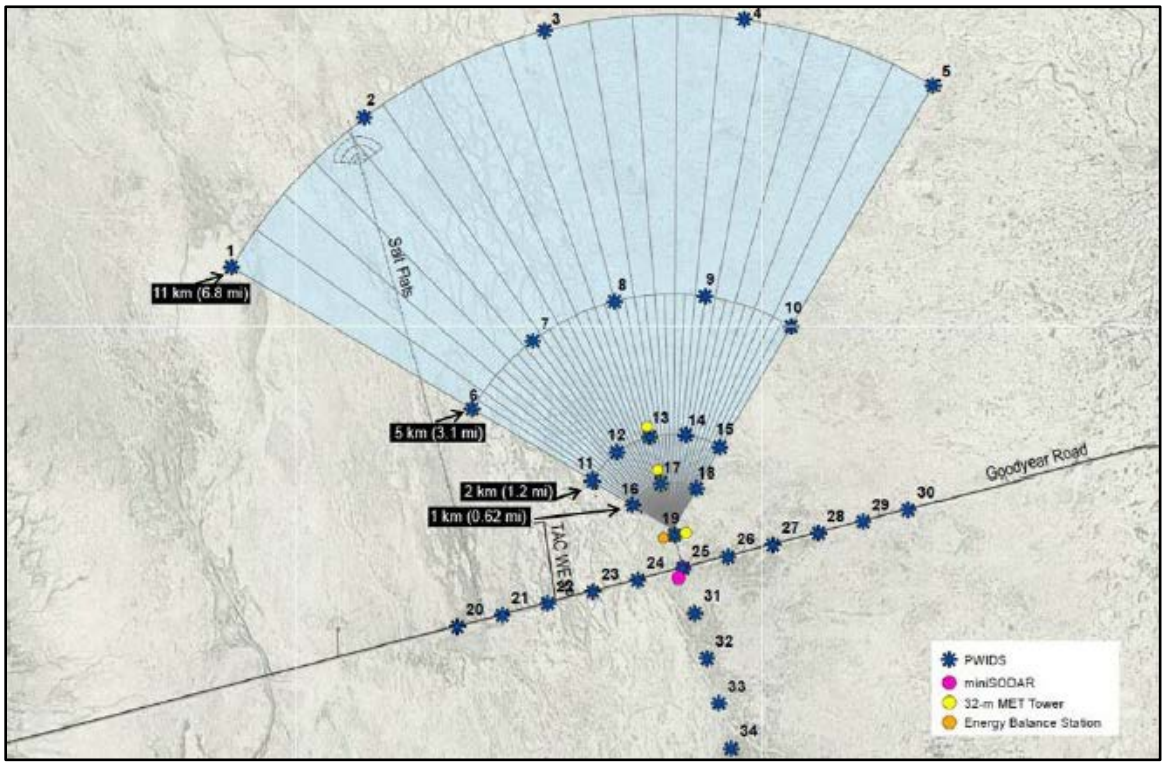

Figure 2-11. Location of the JRII meteorological instrumentation [51].

2.14.4 Discharge System

The discharge system consisted of a storage tank (5.64 m long and 1.37 m diameter) placed at the center of a 25 m diameter concrete dissemination pad, which was itself located near the center[7] of a 122 m by 183 m elevated gravel pad, as shown in Figure 2-12. The concrete pad had a 1-inch lip around its perimeter, to contain any liquid collecting onto its surface. The simulated urban area structures (identified as "Mock Urban Dispersion Area" in the figure) were placed on the gravel pad.

The tank was equipped with a total of 4 discharge ports with 6-inch penetrations: vertical down, vertical up, horizontal, and 45-degrees down from horizontal, as shown in Figure 2-13. The tank was elevated in such a way that the downward-facing release location would be 1 m above ground, placing the tank centerline approximately 1.7 m above

[7] Nicholson et al. [27] reported that the center of the dissemination pad was located 91 m from the upwind edge of the gravel pad, or 0.5 m from its center.

ground. The release was started by triggering a set of explosive bolts on the selected port. Figure 2-14 shows a photograph taken during a vertical release trial.

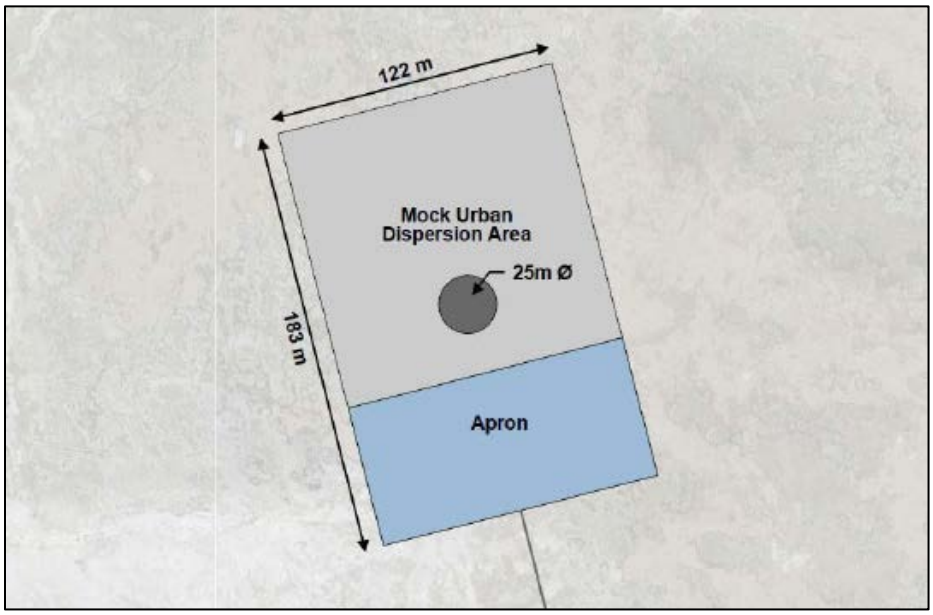

Figure 2-12. Layout of the Jack Rabbit II release and urban dispersion area [51].

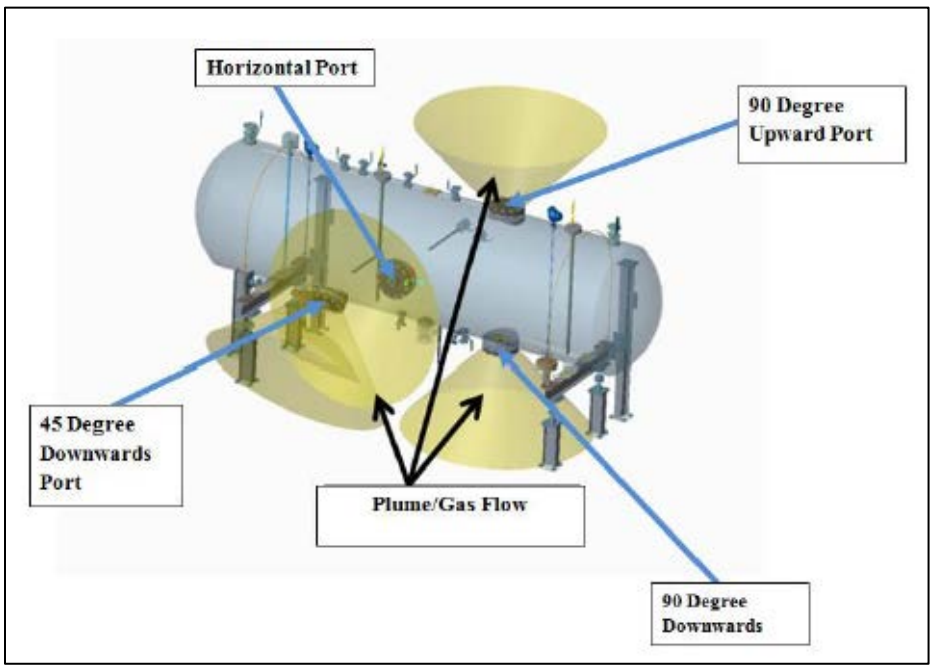

Figure 2-13. Schematic of the JRII chlorine disseminator [51].

Figure 2-14. Photograph of the dissemination tank during the vertical chlorine release in trial No. 8 [22].

Pressure and temperature in the tank were measured throughout the trial, and load cells were used to track the liquid mass in the tank during the discharge.

No significant rainout was observed from the chlorine trials; some degassing from the ground and other anomalies which could suggest rapid phase transition (i.e., sudden vaporization of pockets of liquid) indicated that some liquid chlorine may have deposited on the ground, however, this amount is believed to be negligible [50].

2.14.5 Dispersion Area

The simulated urban area used in the JRII phase 1 trials consisted of a combination of 86 conex containers (between 5.48 and 12.19 m long, and 2.44 m tall), set up for each trial as shown in Figure 2-15. Some of the containers were stacked vertically to simulate a tall structure. The urban area also included two rolling trailers (5.46 x 2.74 m) set up individually in a housing and office configuration and used for interior cast infiltration measurements. Finally, a few vehicles (fire trucks, cars, and one ambulance) were placed at various positions on the urban test grid.

The modular trailers and several of the conex containers were equipped to measure cloud infiltration. Indoor gas migration is outside the scope of the model evaluation for vapor dispersion in LNG facilities; therefore, indoor measurements performed during the JRII trials are not considered in this MVD. For simplicity, all trailers and containers will be assumed to be impermeable to air and gas flow.

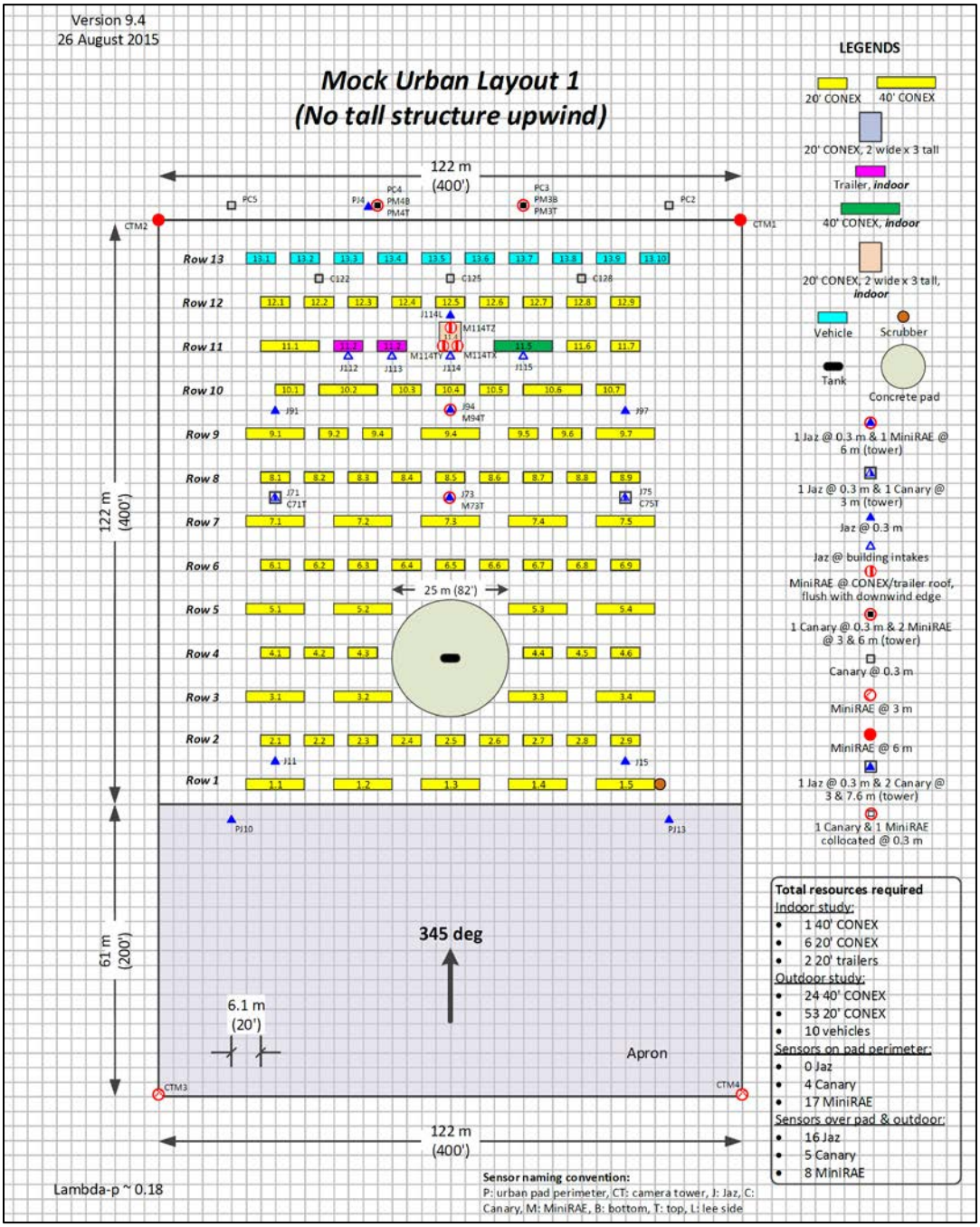

Figure 2-15. JRII urban area layout No. 1 (from JRII Mock Urban Plan, version 9.4, dated 26 August 2015 as obtained from project website[8]).

[8] https://www.uvu.edu/es/jack-rabbit/ last accessed on July 21,2020.

2.14.6 Instrumentation

The Jack Rabbit trials included instrumentation for chemical detection as well as video and photographic documentation of the release and vapor cloud dispersion.

Chemical detection occurred within the simulated urban area and along the edges of the gravel pad (as shown in Figure 2-15 above**Error! Reference source not found.**), and also along concentric arcs with radii of 200 m, 500 m, 1 km, 2 km, 5 km and 11 km from the source (shown in Figure 2-16 through Figure 2-18). Most of the instrumentation spanned an arc of 90° around the array centerline (345° from North), but some instruments were placed crosswind and upwind up to 200 m from the release location, to track any retrograde creep of the dense cloud.

It should be noted that only sensors up to 1 km from the release location were included in this MVD, since measured gas concentrations beyond that arc tended to be below the 0.01% threshold for SPM calculations in this MVD. The far-field sensors will be included in the toxic dispersion database, which will focus on gas dispersion to lower concentrations.

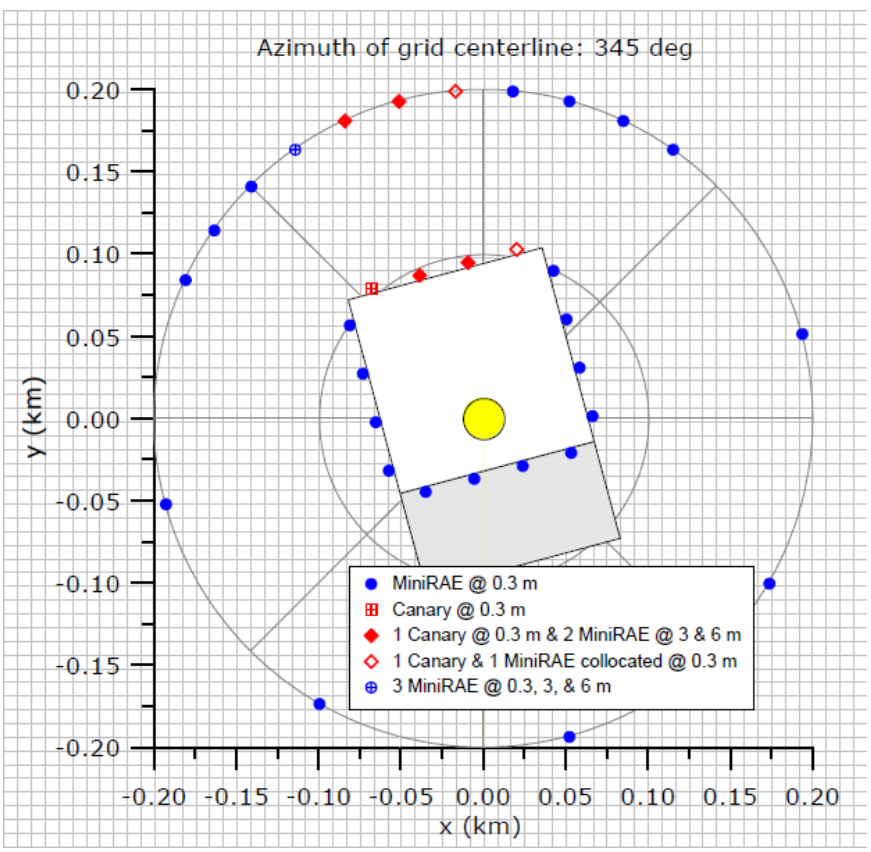

Figure 2-16. Overview of the JRII instrumentation layout (near field) (from JRII Urban Test Plan, version 9.1, dated 24 July 2015 as obtained from project website).

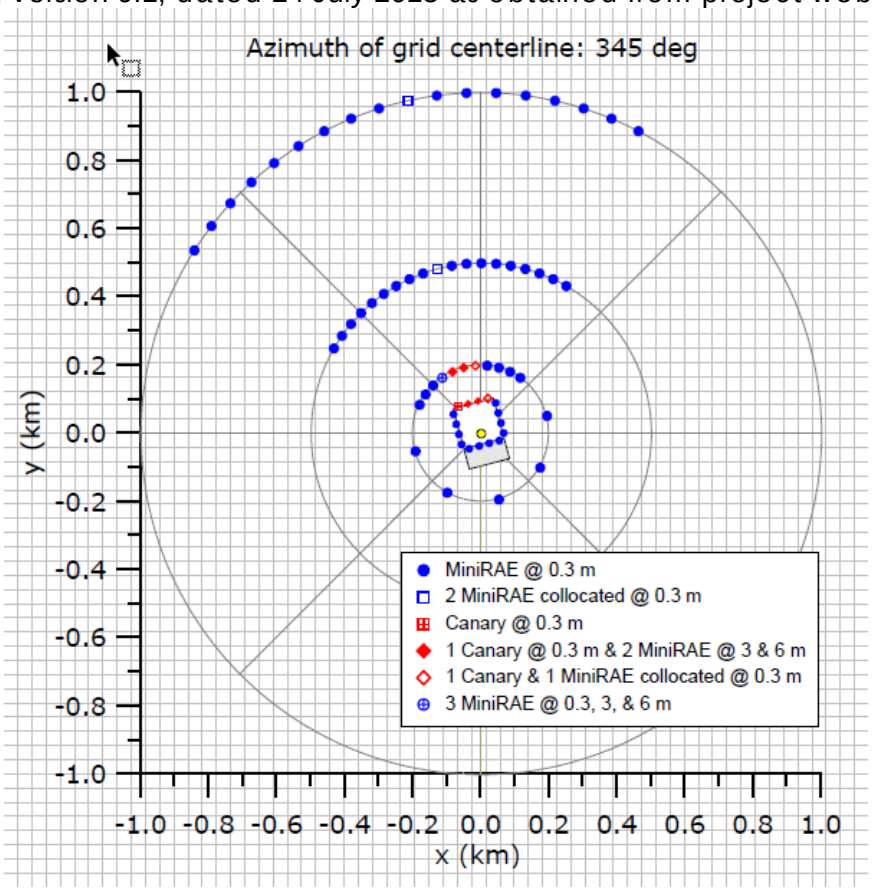

Figure 2-17. Overview of the JRII instrumentation layout (up to 1 km) (from JRII Urban Test Plan, version 9.1, dated 24 July 2015 as obtained from project website).

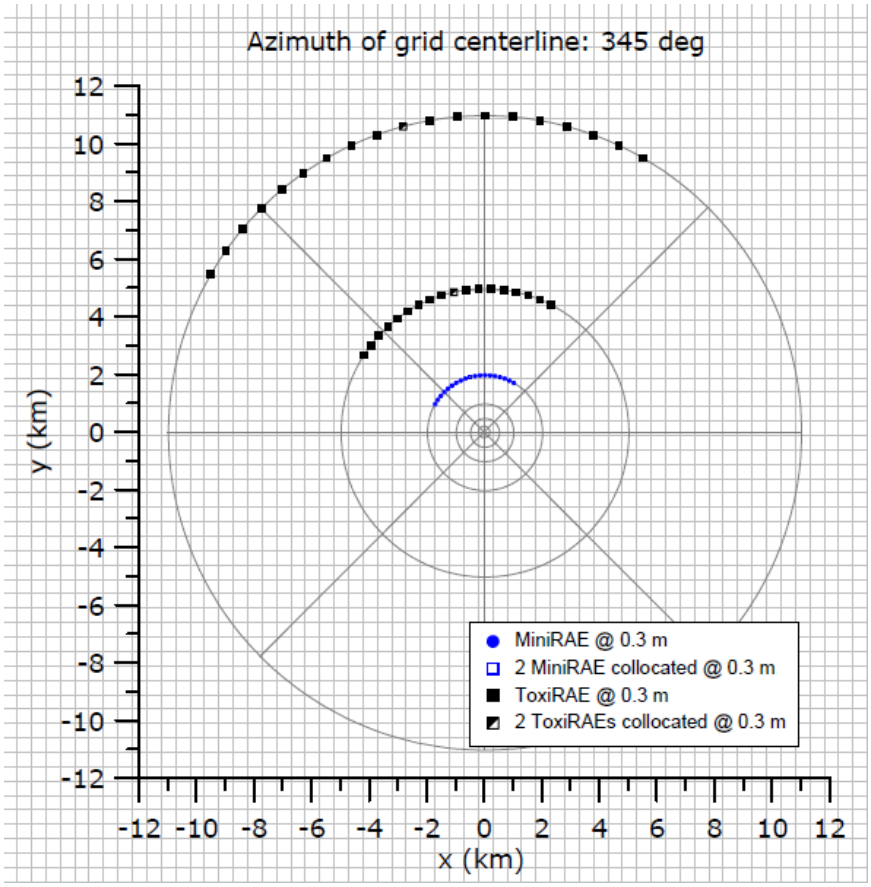

Figure 2-18. Overview of the JRII instrumentation layout (far field) (from JRII Urban Test Plan, version 9.1, dated 24 July 2015 as obtained from project website).

The chlorine detection instrumentation included over 200 detectors of different types, as described in detail by Nicholson et al. [27]. Each detector type spanned a different range of concentrations; the detector distribution was arranged to optimize the measurement accuracy. The placement of individual detectors in each trial is provided in the accompanying spreadsheet.

2.14.7 Experimental Uncertainty

The test series report by Nicholson et al. [27] includes limited information on the accuracy of the various instrumentation. Therefore, for the purpose of estimating uncertainty bands in the MVD, all gas concentration measurements in the JRII series are assumed to have 20% uncertainty.

2.14.8 Test Series Observations and Comments

The JRII trials consisted primarily of downward releases impinging onto the ground. As previously discussed, downward releases are of limited relevance to LNG facility siting scenarios; however, since the JRII test series is currently the only one available involving dispersion of a jet release through an urban-like environment, several trials from these series are included in the MVD. A summary of the trial parameters is provided in Table 2-21, as listed by Byrnes et al. [53]. A more complete set of data for each test is included in the model validation spreadsheet.

Table 2-21. Jack Rabbit II trial parameters.

Test No.	Release Orientation	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atm. Stability Class
JRII 2	Down	166.3	49	4.2	D
JRII 3	Down	125.3	36	3.9	D
JRII 4	Down	162.1	43	2.3	D
JRII 5	Down	166.1	50	2.7	D
JRII 7	45° down	113.3	80	4.5	D
JRII 8	Up	51.3	177	2.2	F

The thermodynamic properties of chlorine most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial. These should be used in models which do not have a species database, or which do not include the released material.

2.14.9 Time Averaging

The time resolution of the measurements during each trial was reported as 0.1 s (1 s for trial 1) for the dissemination tank and 2 s for the chlorine concentration measurements. Therefore, the “short time average” for the JRII simulations is set to 2 s.

The data obtained from the project repository does not include instrument time traces, but only peak measured concentrations and the time at which they occurred (relative to the start of the release). Therefore, long averaging time data cannot be defined for these trials. Table 2-22 lists the short averaging times for the JRII trials included in the MVD.

Table 2-22. Time averaging for the JRII trials.

Trial	Short time avg.
JRII 2	2 s
JRII 3	2 s
JRII 4	2 s
JRII 5	2 s
JRII 7	2 s
JRII 8	2 s

2.14.10 Test Series Sensitivities

The JRII phase 1 trials were used in a modeling effort, summarized by Gant et al. [54], who identified several areas of uncertainty regarding model inputs for these trials. The sensitivity cases specified below are based on a review of the test series data and the previous modeling efforts.

2.14.10.1 Source Term

The source term for the JRII trials consisted of a flashing liquid jet; uncertainty exists regarding the conditions of the stream before it reached the discharge port: release flow rate calculations assuming a metastable liquid (i.e., no flashing inside the tank) were found to overpredict the measured release rate, whereas calculations that allowed flashing before the orifice tended to underpredict the measured flow rate.

Additional uncertainty was identified regarding whether rainout occurred, particularly for releases impinging onto the ground. Spicer and Miller [55], for example, reviewed one of the downward release trials and estimated that approximately 35% of the released material could have rained out. Given the different source term sub-models available in different models (including some that may not have a built-in source term model at all), the base case is defined using the metastable liquid discharge calculation and neglecting rainout; sensitivity cases are specified to include rainout, and to assume a two-phase discharge (either with or without rainout).

The release rate was well characterized through load cell measurements, therefore no sensitivity cases are specified for the release rate.

2.14.10.2 Wind Speed

Wind speed was observed to vary significantly during several of the JRII trials. Since most atmospheric dispersion models assume steady wind conditions, sensitivity cases are specified for high and/or low wind speeds.

2.14.10.3 Atmospheric Stability

Sensitivity cases for atmospheric stability are specified, where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.14.10.4 Roughness Length

The roughness length of the terrain surrounding the test site was estimated as 0.01 m [56]. Given the uncertainty associated with this value and the effect of surface roughness on atmospheric dispersion, sensitivity cases are specified that span one order of magnitude around the base value.

2.14.10.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature, pressure or relative humidity are specified for the JRII trials, given the small fluctuations and uncertainties in the data.

2.14.10.6 Material Properties

The JRII series consisted of releases of pure chlorine. Models that include chlorine in their species database should use the built-in properties in their simulations; models that do not include chlorine should use the thermophysical properties listed in the accompanying spreadsheet. No sensitivity cases are specified.

2.14.10.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-23 and Table 2-24. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-23. Base case and sensitivity cases for the Jack Rabbit II test series (1/2).

Parameter	Case	JRII 2	JRII 3	JRII 4
Source term	Base	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
	S1	Flashing jet, with rainout	Flashing jet, with rainout	Flashing jet, with rainout
Release Rate	Base	166.3 kg/s	125.3 kg/s	162.1 kg/s
Release Duration	Base	49 s	36 s	43 s
Wind Speed (at 2 m height)	Base	4.2 m/s	3.9 m/s	2.3 m/s
Surface Roughness Length	Base	0.01 m	0.01 m	0.01 m
	R1	0.003 m	0.003 m	0.003 m
	R2	0.03 m	0.03 m	0.03 m
Atmospheric Stability	Base	D	D	D
	A1	-	-	E
Ambient Temperature	Base	22.7°C	22.5°C	22.5°C
Ambient Pressure	Base	0.86 atm	0.86 atm	0.86 atm
	P1	1 atm	1 atm	1 atm
Relative Humidity	Base	33.6%	30.3%	26.9%
Stream Composition	Base	Chlorine = 100%	Chlorine = 100%	Chlorine = 100%

Table 2-24. Base case and sensitivity cases for the Jack Rabbit II test series (2/2).

Parameter	Case	JRII 5	JRII 7	JRII 8
Source term	Base	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
	S1	Flashing jet, with rainout	Flashing jet, with rainout	Flashing jet, with rainout
Release Rate	Base	166.1 kg/s	113.3 kg/s	51.3 kg/s
Release Duration	Base	50 s	80 s	177 s
Wind Speed (at 2 m height)	Base	2.7 m/s	4.5 m/s	2.2 m/s
Surface Roughness Length	Base	0.01 m	0.01 m	0.01 m
	R1	0.003 m	0.003 m	0.003 m
	R2	0.03 m	0.03 m	0.03 m
Atmospheric Stability	Base	D	D	F
	A1	E	-	E
Ambient Temperature	Base	22.2°C	18.9°C	14.8°C
Ambient Pressure	Base	0.86 atm	0.86 atm	0.86 atm
	P1	1 atm	1 atm	1 atm
Relative Humidity	Base	26.5%	56.2%	26.5%
Stream Composition	Base	Chlorine = 100%	Chlorine = 100%	Chlorine = 100%

2.15 Kit Fox

Experimental campaign	Kit Fox (KF)
Test dates:	August 1995
Test location:	Frenchman Flat, Nevada
Number of tests:	52
Tests performed by:	Desert Research Institute and Western Research Institute
Brief description:	Carbon dioxide released vertically at low velocity, with dispersion over flat terrain. Artificial roughness elements were introduced to approximate an industrial facility, at 1/10 scale. Two sets of roughness elements distributions were tested.
References:	Western Research Institute, 1998 [57], [58] Hanna et al., 1999 [59] Hanna and Steinberg, 2001 [60]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable
Release Type:	Low-momentum
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**3.0**
Relevance:	4
Material:	2
Scale:	3
Repeatability:	2
Data Quality/Availability:	4

2.15.1 Description

The Kit Fox (KF) test series consists of 52 releases of carbon dioxide (CO_2) dispersing through an array of obstacles intended to represent an industrial site at 1/10 of full scale [60]. CO_2 was released upwards from ground level, at flow rates of approximately 1.6 to 4 kg/s through a 2.25 m^2 area. The release duration varied between approximately 20 seconds (puff) and 3-7 minutes (continuous). CO_2 concentration measurements were performed at several locations and elevations along four rows, at 25, 50, 100, and 225 m downwind of the release.

2.15.2 Test Series Grouping and Rating

The Kit Fox test series involved the release of gaseous carbon dioxide from a ground-level opening measuring 1.5 m by 1.5 m. The resulting cloud dispersed over flat terrain; however, two arrays of small obstacles were added to approximate the roughness of an industrial site and neighboring areas, at a 1/10 scale. For the purpose of categorizing the test series, the obstacle arrays do not represent an "obstruction" or a "complex geometry". The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Low-momentum
- Dispersion Area: Unobstructed

The ground-level source term behaves similarly to the vapor clouds from liquid spills, which represent required siting scenarios. Additionally, the roughness arrays are intended to approximate the effect of structures and equipment in industrial facilities. Therefore, the Kit Fox series is considered more than relevant to the purpose of this MVD ("Relevance" rating = 4). Carbon dioxide is not a material used in LNG facilities; however, the use of CO_2 to produce dense gas clouds in scaled experiments is well established ("Material" rating = 2). The scaling factor of 1/10 is considered acceptable ("Scale" rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). Measurements were performed at four different downwind locations, and each location included several sensors distributed crosswind and at different elevations. The MDA database includes data for each measurement sensor, from both the weather and dispersion arrays ("Data quality/availability" rating = 4).

Overall, the Kit Fox series is rated at 3.0, which meets the "acceptable" threshold; therefore, the Kit Fox series is included in the flammable dispersion MVD. It should be noted that the Kit Fox series was previously included in the Modeler's Data Archive [21] as well as in model developers' internal validation efforts ([13], [61], [62]).

2.15.3 Ambient Conditions

Meteorological instruments were installed on five towers, plus wind vanes at six other locations. Towers were located inside the roughness arrays, as well as on the flat desert surface outside of these areas.

A 24 m tall meteorological tower measured temperature, wind speed and wind direction, and relative humidity at multiple elevations. All data was recorded every 10 seconds (0.1 Hz frequency). The temperature and wind velocity measured by a tower located 20 m upwind of the release location were used to calculate the atmospheric boundary layer parameters for each trial. The wind speed and direction for each trial were obtained from measurements at 2 m above ground, at a weather station 50 m downwind of the release location, averaged over approximately a 1-minute interval.

2.15.4 Discharge System

CO_2 gas was released vertically at a nearly constant rate from a 1.5m x 1.5m area source near the middle of the scaled industrial site. CO_2 was stored at ambient temperature and approximately 125 psig pressure [57]. The discharge piping ran underground and was connected to a release box, measuring 1.5 m x 1.5 m x 1 m deep, placed such that the top of the box would be flush with the terrain. A porous insert was placed within the release box to help distribute the CO_2 flow and obtain a homogeneous vertical velocity at the top surface. Three RTD sensors measured the CO_2 temperature inside the box. A schematic of the discharge system is shown in Figure 2-19.

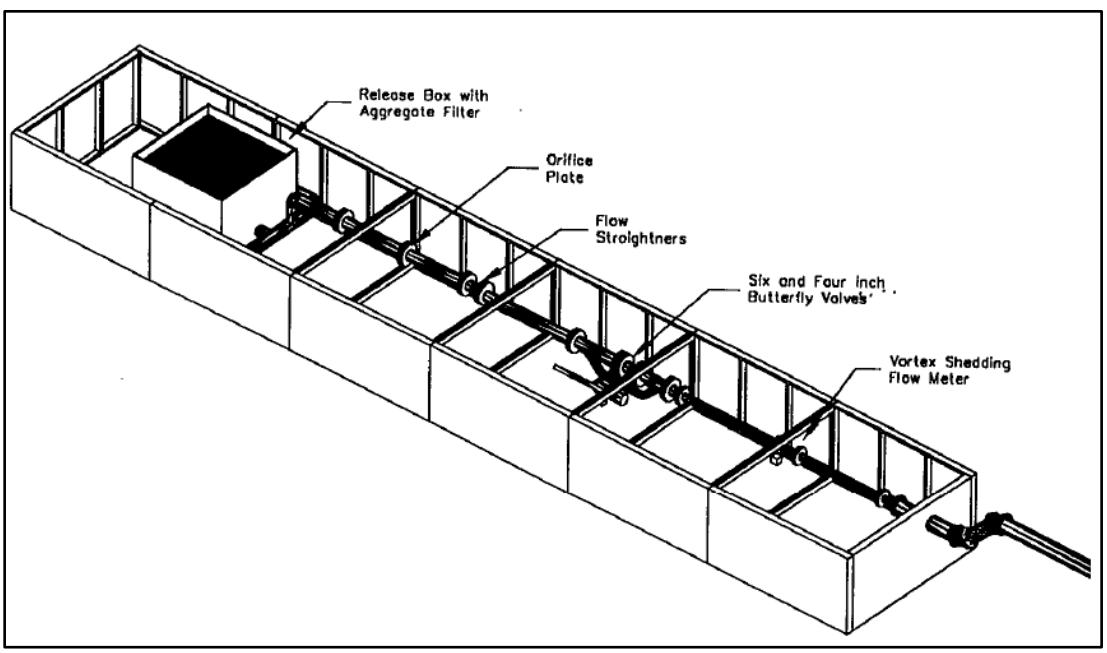

Figure 2-19. Schematic of the Kit Fox discharge system [57].

The discharge flow rate was measured by a vortex shedding flow meter with an accuracy of 1% of full rated flow, or 0.075 kg/s. A second flow rate measurement was provided by a 4.5-in diameter orifice in the discharge line. The two sets of measurements are listed in the WRI report [57] and show very good agreement (within 2-3%).

2.15.5 Dispersion Area

The entire experimental set-up was intended to represent an industrial site at about 1/10 of full scale. For that purpose, three sets of obstacles were installed to develop:

- A Uniform Roughness Area (URA) array, with surface roughness representative of the areas surrounding an industrial facility;
- An Enhanced Roughness Pattern (ERP) array, which simulated the actual industrial facility; and
- A row of spires, to "trip" the boundary layer and accelerate its development.

The URA roughness array was constructed of 6,600 rectangular sections of plywood perpendicular to the mean flow direction (corresponding to 230° from North); each element was 0.8 m wide by 0.2 m tall, and the elements were spaced 2.4 m downwind and 2.4 m laterally. The URA array spanned a length of 314 m (in the direction of mean flow) and a width of 120 m (centered on the release location. The leading edge of the URA was 89 m upwind of the release location.

The ERP roughness array was constructed of 75 square plywood baffles, also perpendicular to the mean flow direction; each baffle was 2.4 m wide by 2.4 m tall, and the baffles were spaced 8.5 m downwind and 6.1 m laterally. The ERP array spanned a length of 85 m (in the direction of mean flow) and a width of 39 m (centered on the release location. The leading edge of the ERP was 50 m upwind of the release location. The ERP elements were removed during the 33 experiments that comprised Kit Fox trials 6-8.

A row of 38 spires was placed, perpendicular to the mean flow direction, at the leading edge of the URA. Each spire consisted of a vertical panel, 4.88 m tall and tapering in width from 47.6 cm at the base to 12.1 cm at the top. The spires were spaced 3.25 m apart and spanned the full width of the URA.

Figure 2-20 shows the layout of the roughness elements relative to the release location. Note that both URA and ERP elements were staggered from one row to the next, to avoid channeling flow between rows.

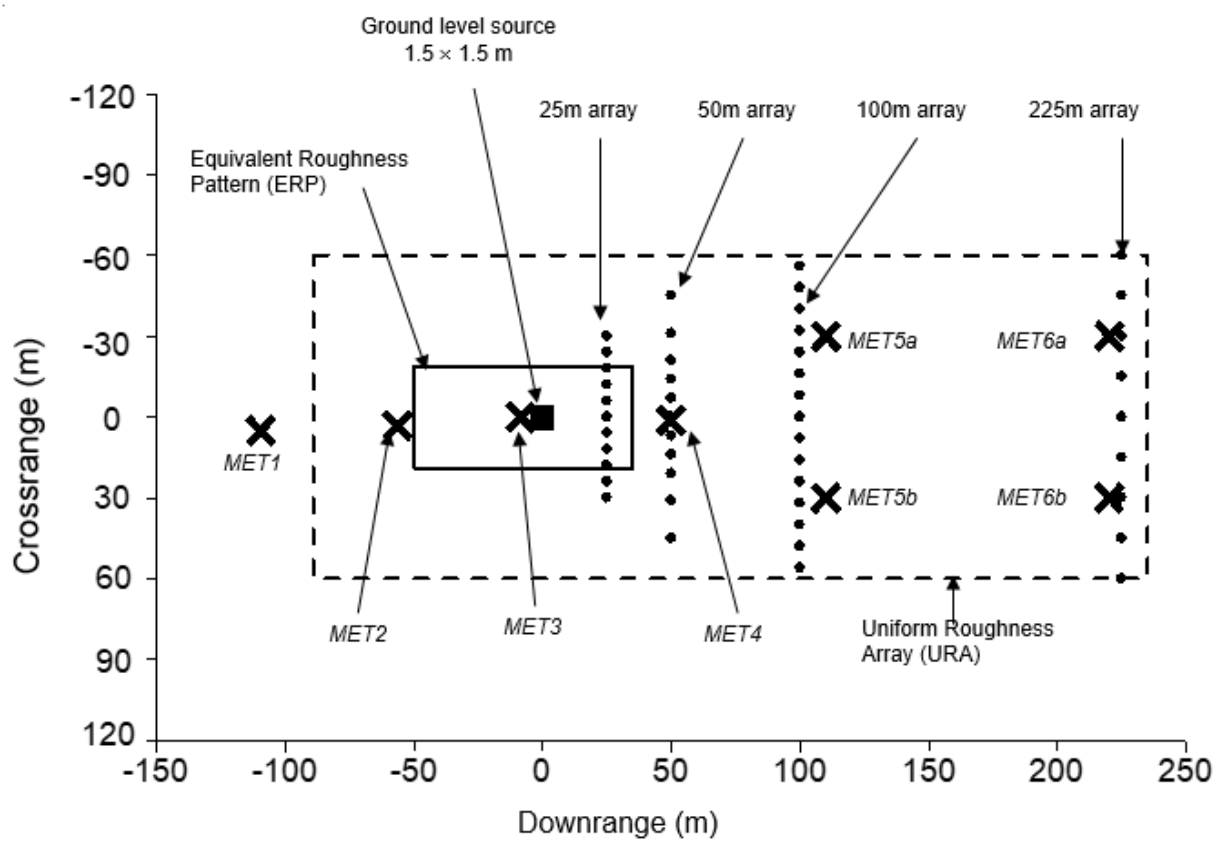

Figure 2-20. Schematic of the Kit Fox dispersion area (adapted from [21]).

2.15.6 Instrumentation

The Kit Fox trials used both high-concentration (up to 150,000 ppm) and low-concentration (up to 20,000 ppm) solid-state infrared carbon dioxide sensors. All CO_2 sensors recorded gas concentration at 1 Hz.

A total of 84 sensors were placed on four downwind rows (25, 50, 100, and 225 m); most of the sensors were placed near the ground (0.3 m elevation along the nearest row, 0.5 m elevation along the other rows), while others were mounted on towers at elevations between 0.6 and 10 m. The position of each sensor during the Kit Fox trials is provided in the accompanying spreadsheet.

2.15.7 Experimental Uncertainty

The manufacturer's reported accuracy for the CO_2 sensors is 1% of full-scale; however, the error analysis during pre-test calibration showed uncertainties up to approximately 20%. Therefore, an experimental uncertainty of 20% is used in the MVD.

2.15.8 Test Series Observations and Comments

The Kit Fox test series included both short-duration (puff) and long-duration (continuous) releases. Only continuous releases are considered here, as they more accurately reflect the type of scenarios required for LNG facility siting.

Not all the trials performed during the Kit Fox test series produced useful data, due to changes in wind direction carrying the cloud outside the measurement area. Based on a review of the test series report, 8 of the 18 continuous releases provided sufficient data and thus included in this MVD. A summary of the test parameters for these 8 trials is provided in Table 2-25. A more complete set of data for each trial is included in the model validation spreadsheet.

Table 2-25. Kit Fox test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atmospheric Stability Class	Roughness Blocks
KF 5-3	3.9	120	2.6 @ 2 m	D	ERP + URA
KF 5-4	3.7	120	2.2 @ 2 m	E	ERP + URA
KF 6-4	1.8	120	4.1 @ 2 m	D	URA only
KF 6-5	1.9	120	3.2 @ 2 m	E	URA only
KF 6-6	2.1	180	2.3 @ 2 m	E	URA only
KF 6-9	1.5	300	1.8 @ 2 m	F	URA only
KF 7-3	1.7	180	3.0 @ 2 m	E	URA only
KF 8-8	1.6	120	3.4 @ 2 m	E	URA only

The thermodynamic properties of CO_2 most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial. These should be used in models which do not have a species database, or which do not include the released material.

2.15.9 Time Averaging

The data included in the MDA database, which is used in this MVD, consists of the calibrated data at 1 Hz frequency. The short averaging time is therefore 1 s for each trial. The long averaging time is set to the duration of the release.[9] Table 2-26 summarizes the short and long time averaging for the KF trials.

Table 2-26. Time averaging for the Kit Fox trials.

Trial	Short time avg.	Long time avg.
KF 5-3	1 s	120 s
KF 5-4	1 s	120 s
KF 6-4	1 s	120 s
KF 6-5	1 s	120 s
KF 6-6	1 s	180 s
KF 6-9	1 s	300 s
KF 7-3	1 s	180 s
KF 8-8	1 s	120 s

2.15.10 Test Series Sensitivities

The Kit Fox test series was included in previous model evaluation efforts. However, no sensitivity studies were performed to evaluate the effects of uncertainties in the model input parameters. The following sensitivity cases are based on a review of available data.

2.15.10.1 Source Term

CO_2 was introduced in gaseous form and at low velocity; the flow rate was measured by two independent methods, with good agreement. Therefore, no sensitivity cases are specified for the release rate or other source term characteristics.

2.15.10.2 Wind Speed

No sensitivity cases are specified to wind speed.

[9] It should be noted that the MDA lists a long averaging time of 20 s for all Kit Fox trials.

2.15.10.3 Atmospheric Stability

Sensitivity cases for atmospheric stability are specified, for trials where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.15.10.4 Roughness Length

Surface roughness in the KF trials was affected by design, by the roughness arrays (ERP and URA). The roughness due to the URA alone was calculated by WRI [58] as 0.03 m, with an uncertainty of approximately 10%. The roughness due to the combined ERP and URA configuration was calculated as 0.3 m. However, Hanna et al. [59] later revised the surface roughness estimates based on their analysis of the KF trial data and attempts to model those trials using the HEGADAS software; their calculated values are 0.12 m for the ERP+URA configuration, and 0.01 m for the URA alone. They also included sensitivity cases with roughness lengths of 0.07 m and 0.02 m, respectively, for the ERP+URA and URA trials.

2.15.10.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature, pressure or relative humidity are specified for the Kit Fox trials, given the small fluctuations and uncertainties in the data.

2.15.10.6 Material Properties

The KF trials released pure CO_2. Models that include CO_2 in their species database should use the built-in properties in their simulations; models that do not include CO_2 should use the thermophysical properties listed in the accompanying spreadsheet. No sensitivity cases are specified.

2.15.10.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-27 and Table 2-28. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided within the model questionnaire.

Table 2-27. Base case and sensitivity cases for the Kit Fox test series (1/2).

Parameter	Case	KF 5-3	KF 5-4	KF 6-4	KF 6-5
Source term	Base	Low-momentum gas	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
Release Rate	Base	3.9 kg/s	3.7 kg/s	1.8 kg/s	1.9 kg/s
Release Duration	Base	120 s	120 s	120 s	120 s
Wind Speed (at 2 m height)	Base	2.6 m/s	2.2 m/s	4.1 m/s	3.2 m/s
Surface Roughness Length	Base	0.12 m	0.12 m	0.01 m	0.01 m
	R1	0.07 m	0.07 m	0.02 m	0.02 m
Atmospheric Stability	Base	D	E	D	E
	A1	E	F	-	D
Ambient Temperature	Base	33.1°C	31.4°C	36.7°C	36.0°C
Ambient Pressure	Base	0.89 atm	0.89 atm	0.89 atm	0.89 atm
	P1	1 atm	1 atm	1 atm	1 atm
Relative Humidity	Base	15%	16%	14%	14%
Stream Composition	Base	CO_2 = 100%	CO_2 = 100%	CO_2 = 100%	CO_2 = 100%

Table 2-28. Base case and sensitivity cases for the Kit Fox test series (2/2).

Parameter	Case	KF 6-6	KF 6-9	KF 7-3	KF 8-8
Source term	Base	Low-momentum gas	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
Release Rate	Base	2.1 kg/s	1.5 kg/s	1.7 kg/s	1.6 kg/s
Release Duration	Base	180 s	180 s	300 s	120 s
Wind Speed (at 2 m height)	Base	2.3 m/s	1.8 m/s	3.0 m/s	3.4 m/s
Surface Roughness Length	Base	0.01 m	0.01 m	0.01 m	0.01 m
	R1	0.02 m	0.02 m	0.02 m	0.02 m
Atmospheric Stability	Base	E	F	E	E
	A1	F	E	D	D
Ambient Temperature	Base	35.4°C	34.0°C	37.9°C	36.7°C
Ambient Pressure	Base	0.89 atm	0.89 atm	0.89 atm	0.89 atm
	P1	1 atm	1 atm	1 atm	1 atm
Relative Humidity	Base	14%	14%	10%	15%
Stream Composition	Base	CO_2 = 100%	CO_2 = 100%	CO_2 = 100%	CO_2 = 100%

2.16 Lathen/EEC

Experimental campaign	Lathen (EEC)
Test dates:	October 1988 – September 1989
Test location:	Lathen, Germany
Number of tests:	58
Tests performed by:	TüV Norddeutschland and Risø
Brief description:	Pressurized propane releases with different configurations, including: horizontal and vertical jets; no-momentum cyclone source; a mobile jet source; and a pure gas source. Obstacles were placed in different configurations (straight line or arc) and concentration measurements were performed both in front and behind the obstacles.
References:	Nielsen and Jensen, 1991 [63] Nielsen and Ott, 1996 [23]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Flammable (non-LNG)
Release Type:	Flashing Jet
Dispersion Area:	Unobstructed; Obstructed
Test series rating	
Overall:	**3.6**
Relevance:	5
Material:	5
Scale:	3
Repeatability:	2
Data Quality/Availability:	3

2.16.1 Description

The Lathen test series, also known as BA-Propane or EEC (therefore identified by EEC throughout this report), consists of over 50 propane releases with different configurations, including: horizontal and vertical jets; no-momentum cyclone source; a mobile jet source; and a pure gas source. The release rates were on the order of 0.2-3 kg/s, for a duration of approximately 3-5 minutes. Barriers were placed in different configurations (straight line or arc), and concentration measurements were performed both in front and behind the obstacles.

2.16.2 Test Series Grouping and Rating

The Lathen (EEC) test series involved the release of propane, liquefied under pressure and discharged downwind through an orifice of approximately 0.6-inch diameter. The resulting cloud dispersed over flat terrain, but barriers were placed approximately 50 m from the release to obstruct the cloud dispersion. The test series therefore fits in the following categories:

- Material: Flammable (non-LNG)
- Release Type: Flashing Jet
- Dispersion Area: Obstructed

The release of pressurized liquids through orifices, with dispersion affected by obstructions (e.g., vapor barriers) is a common scenario for siting studies ("Relevance" rating = 5). Propane is used as a refrigerant (pure or mixed with other hydrocarbons) in many LNG liquefaction facilities, therefore, the dispersion of propane releases is frequently modeled in siting studies ("Material" rating = 5). However, the release flow rates and the downwind distances over which the cloud dispersion was measured are smaller than typically modeled ("Scale" rating = 3).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). Limited information is available on the instrumentation and quality of the data recorded during the EEC trials, but the REDIPHEM database includes data for each measurement sensor, reported at 1 s intervals ("Data quality/availability" rating = 3).

Overall, the EEC series is rated at 3.6, which is above the "acceptable" threshold; therefore, the EEC test series is considered suitable for inclusion in the flammable dispersion MVD.

2.16.3 Ambient Conditions

Ambient conditions (wind speed and direction, turbulence and air temperature) were recorded for each trial from instrumentation mounted on a set of 6 m tall masts. In some cases, however, the wind measurements were missing, and the speed and direction were obtained from a separate station which logged 10-min average values of speed and direction. Prior to each release, the ambient humidity and temperature were measured with a hand held psychrometer, and a note was made on the cloud cover [23].

2.16.4 Discharge System

At least four different gas sources were used in the Lathen experiments, as described by Nielsen and Ott [23] and shown schematically in Figure 2-21:

1. A jet source which released pressurized liquid propane through a nozzle to generate a flashing jet. In some of the trials, the nozzle was pointed in the vertical direction. No liquid pool formed on the ground.
2. A cyclone release source, with no net momentum. About 33% of the liquid material separated inside the cyclone and formed a pool on the ground.
3. A mobile jet source, which released a jet directed towards the ground. The release rates were lower than for the fixed jet source, and little rainout was observed.
4. A pure gas source, obtained by evaporating the liquified propane inside a large reservoir and allowing the evaporated gas to exit at the top. The release pressure and temperature of this source were not measured.

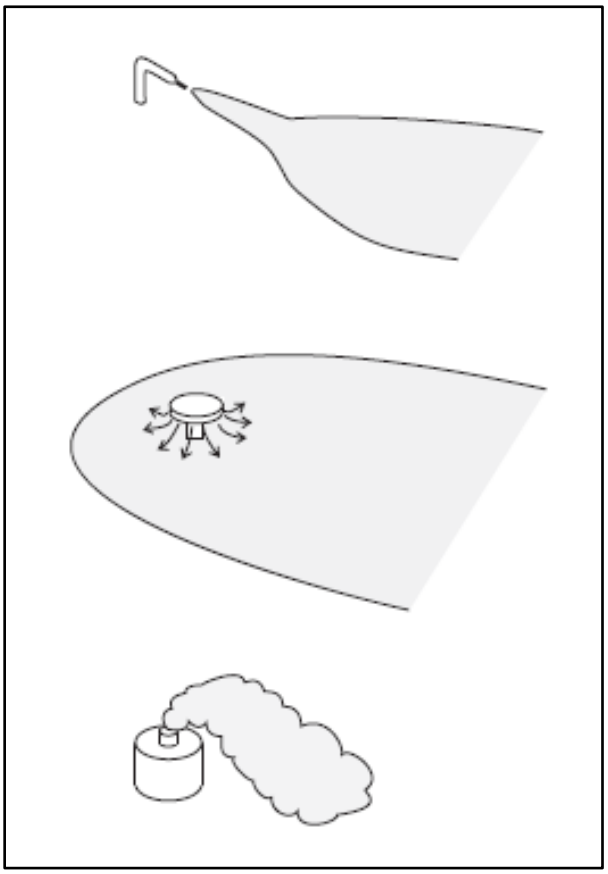

Figure 2-21. Schematic of the EEC discharge systems (types 1, 2 and 4, respectively, from top to bottom) [23].

Given the large number of low-momentum releases available from other test series, the focus for the EEC series was placed on jet releases. All EEC jet releases included in this database occurred from a 0.6-in (15.5 mm) diameter orifice, oriented horizontally downwind at 0.5 m above ground.

2.16.5 Dispersion Area

The EEC trials were aimed at evaluating the effect of solid barriers on the dispersion of dense gas clouds; the test series was designed to study gas flow over a linear or curved wall or between two parallel walls. Hence, the test series was intended to be flexible in the type of release, placement of barriers and instrumentation.

The gas cloud was expected to be flat and wide, so the barriers consisted of long stretches of 2 m high heavy curtains. The various curtain configurations were placed approximately 50 m from the release. Before each trial, the curtains were mounted only

on the part of the obstacle configuration which was exposed to gas based on the wind direction. Sometimes, only every other curtain in the obstacle lines was mounted, giving a 50% overall porosity. The curtains were designed to be removed during the experiment by pulling a wire, with the intent to obtain a comparison of dispersion with and without obstacles, for the same source term and weather. The variable configuration is not considered relevant to siting studies; however, the use of barriers to control vapor cloud dispersion is currently quite common in LNG facilities, therefore, several EEC trials with barrier removal are included in the MVD. However, only data prior to the removal of the barriers is used for model comparisons.

2.16.6 Instrumentation

A total of 44 catalytic and IR sensors were used to measure propane concentration during the EEC trials. These measurements were performed near ground level in a flexible array, whose arrangement was varied depending on the trial. The catalytic gas sensors were reported to have a response time of approximately 10 seconds, even though data was sampled at 1 Hz.

Gas concentration measurements (in addition to temperature, wind speed, wind direction and turbulence) were also performed on the meteorological masts, which were placed upwind and downwind of the walls, perpendicular to the expected wind direction; the concentration measurements were at 1, 2, and 4 m above ground. Figure 2-22 shows a schematic of the barrier and mast layout for two of the test configurations. Given the flexible arrangement of the trials, the user is strongly encouraged to review the instrument location in the MVD spreadsheet for each trial.

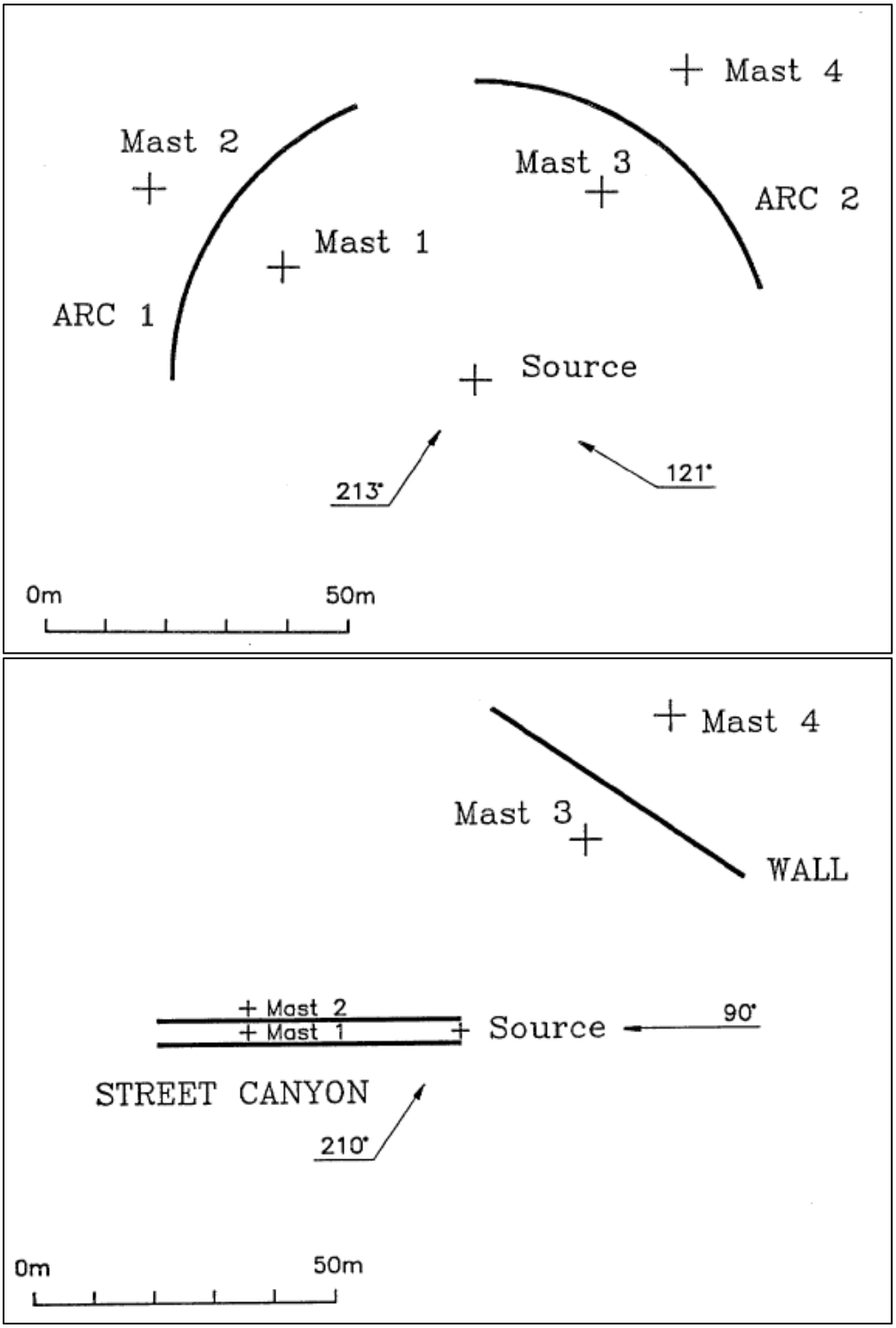

Figure 2-22. Schematic of two EEC test configurations: (top) May 1989; (bottom) August-September 1989 [63].

2.16.7 Experimental Uncertainty

No information was found in the available references regarding the uncertainty of the gas concentration measurement. Therefore, an overall experimental uncertainty of 20% is specified in the accompanying spreadsheet.

2.16.8 Test Series Observations and Comments

The REDIPHEM database includes data from 51 trials form the EEC series, including information regarding the discharge, barrier and instrumentation layout. Only a subset of the EEC trials is included in this MVD. Specifically, the focus was placed on trials involving horizontal jet releases and obstructed dispersion. Additionally, it must be noted that for trials during which the barrier was removed, only data prior to the barrier removal was considered. A summary of the test parameters is provided in Table 2-29**Error! Reference source not found.**. A more complete set of data for each test is included in the model validation spreadsheet.

Table 2-29. Lathen (EEC) test parameters.

Test No.	Release Rate [kg/s]	Release Duration [s]	Wind Speed [m/s]	Atm. Stability Class	Barriers
EEC 07	2.9	200	4.3 @ 3.3 m	D	Curved (removed at 90 s)
EEC 08	2.9	250	4.2 @ 6 m	C	Curved, 50% porous (removed at 120 s)
EEC 17	2.9	160	3.9 @ 3.3 m	D	Curved (removed at 90 s)
EEC 18	2.9	180	4.4 @ 3.3 m	D	Curved, 50% porous (removed at 120 s)
EEC 54	3.0	300	2.3 @ 6 m	D	Linear
EEC 55	3.0	360	3.2 @ 6 m	D	Linear (removed at 185 s)
EEC 56	3.0	360	2.4 @ 6 m	C	Linear, 50% porous (removed at 180 s)

As shown in the accompanying spreadsheet, the EEC sensors were not placed along arcs or lines; however, their placement was such that they could be grouped into a discrete set of arcs by ranges of distances (i.e., all sensors within a 10 m deep arc were grouped together, at a nominal arc distance equal to the center of the band). This approach allows arc-wise maxima and SPMs to be calculated for the EEC trials.

The thermodynamic properties of propane most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial. These should be used in models which do not have a species database, or which do not include the released material.

2.16.9 Time Averaging

Data from the EEC trials is available as part of the REDIPHEM database, where it is presented as 1 Hz time traces. However, the short averaging time is set to 10 s, to match the response time of the catalytic sensors. Long averaging times are not considered meaningful for trials where the barrier was removed before the end of the release, as that action clipped the tail end of the dispersing cloud. Therefore, long averaging times are listed in Table 2-30 only for trials during which the barrier was not removed.

Table 2-30. Time averaging for the Lathen (EEC) trials.

Trial	Short time avg.	Long time avg.
EEC 07	10 s	-
EEC 08	10 s	-
EEC 17	10 s	-
EEC 18	10 s	-
EEC 54	10 s	300 s
EEC 55	10 s	-
EEC 56	10 s	-

2.16.10 Test Series Sensitivities

No previous model evaluation efforts were found that included the EEC trials. Therefore, the following sensitivity cases are based on a review of available data.

2.16.10.1 Source Term

The source term consisted of a flashing jet of propane at known conditions. No rainout was reported. The release rate was reportedly consistent across multiple trials. Therefore, no sensitivity cases to the source term are specified.

2.16.10.2 Wind Speed

No sensitivity cases are specified to wind speed.

2.16.10.3 Atmospheric Stability

Sensitivity cases for atmospheric stability were specified, where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.16.10.4 Roughness Length

The surface roughness was estimated from wind profiles measured in the absence of obstacles or gas release. The REDIPHEM database lists the value as 0.006 m. Given the lack of information on the derivation of this value or its uncertainty, sensitivity cases are specified to span one order of magnitude across the base case.

2.16.10.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature, pressure or relative humidity are specified for the EEC trials, given the small fluctuations and uncertainties in the data.

2.16.10.6 Material Properties

The EEC trials released liquefied propane. Models that include propane in their species database should use the built-in properties in their simulations; models that do not include propane should use the thermophysical properties listed in the accompanying spreadsheet. No sensitivity cases are specified.

2.16.10.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-31 and Table 2-32. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-31. Base case and sensitivity cases for the Lathen (EEC) test series (1/2).

Parameter	Case	EEC 07	EEC 08	EEC 17	EEC 18
Source term	Base	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
Release Rate	Base	2.9 kg/s	2.9 kg/s	2.9 kg/s	2.9 kg/s
Release Duration[10]	Base	90 s	120 s	90 s	120 s
Wind Speed	Base	4.3 m/s @ 3.3 m	4.4 m/s @ 6 m	3.9 m/s @ 3.3 m	4.4 m/s @ 3.3 m
Surface Roughness Length	Base	0.006 m	0.006 m	0.006 m	0.006 m
	R1	0.001 m	0.001 m	0.001 m	0.001 m
	R2	0.01 m	0.01 m	0.01 m	0.01 m
Atmospheric Stability	Base	D	C	D	D
	A1	-	D	-	-
Ambient Temperature	Base	12.0°C	15.0°C	15.0°C	16.0°C
Ambient Pressure	Base	1 atm	1 atm	1 atm	1 atm
Relative Humidity	Base	72%	37%	55%	60%
Stream Composition	Base	Propane = 100%	Propane = 100%	Propane = 100%	Propane = 100%

[10] Until barrier removal, where applicable

Table 2-32. Base case and sensitivity cases for the Lathen (EEC) test series (2/2).

Parameter	Case	EEC 54	EEC 55	EEC 56
Source term	Base	Flashing jet, no rainout	Flashing jet, no rainout	Flashing jet, no rainout
Release Rate	Base	3.0 kg/s	3.0 kg/s	3.0 kg/s
Release Duration[11]	Base	90 s	120 s	90 s
Wind Speed	Base	2.0 m/s @ 6 m	3.2 m/s @ 6 m	2.4 m/s @ 6 m
Surface Roughness Length	Base	0.006 m	0.006 m	0.006 m
	R1	0.001 m	0.001 m	0.001 m
	R2	0.01 m	0.01 m	0.01 m
Atmospheric Stability	Base	D	D	C
	A1	-	-	D
Ambient Temperature	Base	7.7°C	9.9+°C	11.8°C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	100%	99%	100%
Stream Composition	Base	Propane = 100%	Propane = 100%	Propane = 100%

[11] Until barrier removal, where applicable

2.17 Maplin Sands

Experimental campaign	Maplin Sands (MS)
Test dates:	1980
Test location:	Maplin Sands, England
Number of tests:	34
Tests performed by:	Shell Research Ltd.
Brief description:	LNG and LPG spills onto water; unobstructed vapor cloud dispersion over water.
References:	Stewart et al., 2016 [3] Colebrander and Puttock, 1984 [64] Puttock et al., 1982 [65] Ermak et al., 1989 [32]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	LNG
Release Type:	Spill
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**4.0**
Relevance:	5
Material:	5
Scale:	5
Repeatability:	2
Data Quality/Availability:	3

2.17.1 Description

The Maplin Sands test series consisted of 34 spills of liquefied gases (LNG and LPG) onto water; they were conducted at the Maplin Sands site, an area of tidal sands in the estuary of the river Thames. The vapor clouds produced by the evaporation of the liquid spills were tracked as they dispersed over water; Figure 2-23 shows a schematic of the spill area and measurement arcs. Both continuous and instantaneous releases were carried out.

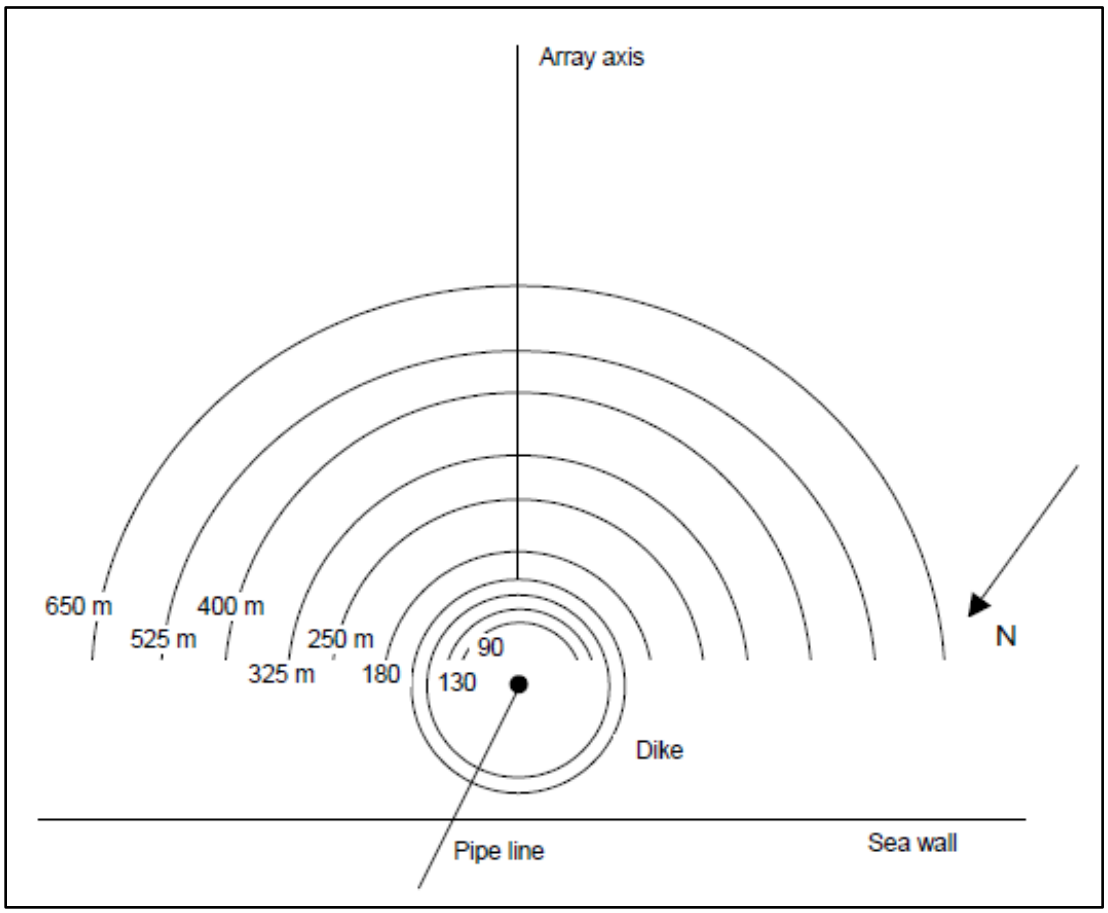

Figure 2-23. Maplin Sands spill area and measurement arcs [3].

2.17.2 Test Series Grouping and Rating

The Maplin Sands trials included in this MVD consisted of spills of LNG onto the water surface. The resulting clouds dispersed over open water, with no obstructions. The test series therefore fits in the following categories:

- Material: LNG
- Release Type: Spill
- Dispersion Area: Unobstructed

Modeling vapor dispersion from LNG spills is a regulatory requirement in siting studies. Therefore, the MS trials are highly relevant to the purpose of this MVD ("Relevance" rating = 5 and "Material" rating = 5). The release flow rates and the downwind distances over which the cloud dispersion was measured scale well with typical facility siting scenarios ("Scale" rating = 5).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). The overall quality and availability of data from the MS trials, for the purpose of this MVD is considered acceptable for the purpose of this MVD ("Data quality/availability" rating = 3).

Overall, the MS series is rated at 4.0, which is above the "acceptable" threshold; therefore, the Maplin Sands test series is considered suitable for inclusion in the flammable dispersion MVD. This conclusion is consistent with the inclusion of the MS series in the LNG spills database [3].

2.17.3 Test Series Observations and Comments

Three trials from the MS test series were included in the LNG spills database; the same trials are included in the current MVD, to provide continuity for models previously evaluated against that database. Table 2-33 lists the main test parameters for the trials included in the flammable dispersion MVD. A more complete set of data for each test is included in the model validation spreadsheet; the data included in the spreadsheet was obtained from the MDA database and the LNG spills database. Additional information on these trials can be found in the references listed in the summary table for the MS test series.

Table 2-33. Maplin Sands test parameters.

Test No.	Spill Rate [kg/s]	Spill Duration [s]	Wind Speed [m/s]	Atm. Stability Class
MS 27	23.2	160	5.5	C-D
MS 34	21.5	95	8.6	D
MS 35	27.1	135	9.8	D

The thermodynamic properties of LNG most frequently needed for dispersion modeling are included in the MVD spreadsheet for each trial, based on the mixture composition provided in the MVD. These should be used in models which do not have a species database, or which do not include the released material.

2.17.4 Time Averaging

The MDA database includes Maplin Sands data based on 3-second running averages. Therefore, the short time averaging for the Maplin Sands trials is set to 3 s, as summarized in Table 2-34.

Table 2-34. Time averaging for the Maplin Sands trials.

Trial	Short time avg.
MS 27	3 s
MS 34	3 s
MS 35	3 s

2.17.5 Test Series Sensitivities

The boundary conditions and source data for the base case are specified as in the LNG spill database [3]. The sensitivity cases are specified based on a review of the test series references and the DEGADIS model evaluation report by FERC [20].

2.17.5.1 Source Term

The source sensitivity for the MS trials was evaluated by FERC using three different approaches: a time-varying LNG pool source model and two different steady state pools with vaporization rates of 0.167 kg/m^2-s and 0.085 kg/m^2-s, respectively. For consistency, the same values are applied in this MVD. The time-varying pool model is taken as the base case, since most current dispersion models include this source term capability.

No sensitivity cases are specified for the release rates.

2.17.5.2 Wind Speed

FERC performed sensitivity runs to wind speed for the Maplin Sands trials, due to fluctuations in the wind speed during each trial. The high and low cases were set, respectively, to the upper and lower quartile of the wind speed data. The same sensitivity

cases are specified in this MVD, for consistency with previous validation efforts. In all cases, the wind speed and direction should be kept steady throughout the simulation.

2.17.5.3 Atmospheric Stability

Sensitivity cases for atmospheric stability were specified, where the ambient conditions (wind speed, cloud cover, etc.) produced uncertainty in the representative Pasquill-Gifford class.

2.17.5.4 Roughness Length

Stewart et al. reported a value of 0.0003 m for the Maplin Sands trials, consistent with the MDA but approximately one order of magnitude higher than other reports ([32], [64]). FERC suggested sensitivity cases spanning an order of magnitude across the base case. The same sensitivity range is specified in this MVD.

2.17.5.5 Temperature, Pressure and Humidity

No sensitivity cases to ambient temperature are required for the Maplin Sands trials, given the small fluctuations and uncertainties in the data.

The ambient pressure during the MS trials was not specified and was therefore assumed to be 1 atmosphere. Therefore, no sensitivity to ambient pressure is required for the MS trials.

FERC specified sensitivity cases to relative humidity for some of the MS trials, on the basis of some inconsistency between the values reported in the original MS reports and later publications [66]. Therefore, relative humidity is included in this MVD as a sensitivity parameter for the MS trials.

2.17.5.6 Material Properties

The Maplin Sands trials involved spills of LNG. Colebrander and Puttock [64] provided the actual LNG composition used in each trial, which is therefore used to define the base case. Given the common (and generally conservative) practice of modeling LNG releases as pure methane, a sensitivity case with 100% methane is included in the MVD.

2.17.5.7 Summary of Sensitivity Cases

Based on the discussion above, the model validation efforts should include the sensitivity cases listed in Table 2-35. If one or more sensitivity cases cannot be run, for example, due to hard-coding of certain parameters in a model, an explanation should be provided in the model questionnaire.

Table 2-35. Base case and sensitivity cases for the Maplin Sands test series.

Parameter	Case	MS 27	MS 34	MS 35
Source term	Base	Spreading pool	Spreading pool	Spreading pool
	S1	Steady pool, 0.167 kg/m^2-s vap. rate	Steady pool, 0.167 kg/m^2-s vap. rate	Steady pool, 0.167 kg/m^2-s vap. rate
	S2	Steady pool, 0.085 kg/m^2-s vap. rate	Steady pool, 0. 085 kg/m^2-s vap. rate	Steady pool, 0.085 kg/m^2-s vap. rate
Release Rate	Base	23.2 kg/s	21.5 kg/s	27.1 kg/s
Wind Speed (at 10 m height)	Base	5.5 m/s	8.6 m/s	9.8 m/s
Surface Roughness Length	Base	0.0003 m	0.0003 m	0.0003 m
	R1	0.001 m	0.001 m	0.001 m
	R2	0.0001 m	0.0001 m	0.0001 m
Atmospheric Stability	Base	D	D	D
	A1	C	C	C
Ambient Pressure	Base	1 atm	1 atm	1 atm
Relative Humidity	Base	53%	72%	63%
	H1	63%	90%	77%
Stream Composition	Base	Methane = 93.2% Ethane = 5.4% Propane = 1.1%	Methane = 95.9% Ethane = 2.6% Propane = 0.9%	Methane = 97.8% Ethane = 1.7% Propane = 0.4%
	C1	Methane = 100%	Methane = 100%	Methane = 100%

2.18 Mock Urban Setting Test (MUST)

Experimental campaign	Mock Urban Setting Test (MUST)
Test dates:	September 2001
Test location:	Dugway Proving Ground
Number of tests:	37
Tests performed by:	Defense Threat Reduction Agency (DTRA)
Brief description:	Pressurized propylene released from a continuous point source or a series of puffs. Vapor cloud dispersed through shipping containers designed to mimic an urban landscape. Propylene concentrations and temperatures measured throughout the urban landscape.
References:	Biltoft, 2001 [67]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-flammable[12]
Release Type:	Gas Jet
Dispersion Area:	Complex geometry
Test series rating	
Overall:	**0**
Relevance:	0
Material:	
Scale:	
Repeatability:	
Data Quality/Availability:	

[12] Even though propylene is a flammable gas, it was used a s a tracer gas in the MUST experiments, therefore all measured concentrations were well below the lower flammable limit. Therefore, for the purpose of this review, propylene is considered non-flammable.

2.18.1 Description

The Mock Urban Setting Test (MUST) was conducted at the U.S. Army Dugway Proving Ground (DPG) Horizontal Grid test site in September 2001. The experimental objective was to acquire meteorological and dispersion data sets at near full-scale for use in urban dispersion model development and validation [68]. The MUST design consisted of a 12 by 10 array of conex shipping containers intended to produce urban-scale roughness over a 200 m^2 area.

Pressurized gaseous propylene was released at flow rates between approximately 150 and 225 L/min (i.e., as a tracer gas) from a nozzle pointed horizontally at a height between 0.15 and 2.7 m above ground. The release duration varied between approximately 4 and 133 minutes via continuous and puff releases. The tracer gas dispersion was measured using fast-response photoionization detectors (PIDs), placed at multiple locations throughout the array. A total of 68 trials (63 continuous releases and 5 multiple puff releases) were completed during the MUST test series.

2.18.2 Test Series Grouping and Rating

The MUST trials consisted of tracer gas releases of propylene, dispersing through an array of shipping containers intended to approximate the effect of dispersion through an urban area. The test series therefore fits in the following categories:

- Material: Non-flammable
- Release Type: Tracer
- Dispersion Area: Complex geometry

Tracer releases are not considered relevant to a model validation database for flammable dispersion since the tracer gas concentrations are well below the typical LFL values. Therefore, the MUST test series is not considered suitable for inclusion in this MVD.

2.19 Porton

Experimental campaign	Porton (HF)
Test dates:	August 2000
Test location:	Porton, England
Number of tests:	12
Tests performed by:	Risø National Laboratory
Brief description:	Pressurized jet releases of anhydrous hydrogen fluoride, dispersing over sloped terrain, under a wide range of ambient conditions. Designed to evaluate the influence of HF thermodynamics on cloud dispersion.
References:	Ott and Jørgensen, 2001 [69] Trégourès et al., 2001 [70]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Non-Flammable
Release Type:	Flashing jet
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**2.6**
Relevance:	4
Material:	2
Scale:	2
Repeatability:	2
Data Quality/Availability:	3

2.19.1 Description

The Porton (HF) test series consists of 12 anhydrous hydrogen fluoride releases designed to evaluate potential buoyancy effects due to HF thermodynamics on the dispersion of the vapor cloud – particularly, enhanced mixing and/or cloud liftoff. HF was released for 3 minutes, at rates of approximately 0.1 kg/s. The cloud dispersed over unobstructed but slightly sloped terrain, with low vegetation. HF concentration measurements were performed at distances up to 2 km from the source.

2.19.2 Test Series Grouping and Rating

The Porton test series involved the release of anhydrous hydrogen fluoride (HF), liquefied under pressure and discharged downwind through a small orifice. The resulting cloud dispersed over unobstructed but slightly sloped terrain. The test series therefore fits in the following categories:

- Material: Non-Flammable
- Release Type: Flashing Jet
- Dispersion Area: Unobstructed

The release of pressurized liquids through orifices, with dispersion affected by terrain features is a very common scenario for siting studies, therefore, the HF trials are relevant to the purpose of this MVD ("Relevance" rating = 4. However, HF is not a material found in LNG facilities; additionally, HF presents peculiar thermodynamic properties that are not representative of any other fluid typically found in LNG facilities ("Material" rating = 2). The small release flow rates and the downwind distances over which the cloud dispersion was measured resulted in concentration measurements well below the range of interest in facility siting scenarios ("Scale" rating = 2).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). No information is available to determine the accuracy of most of the instrumentation. The REDIPHEM database includes data for each measurement sensor, reported at 1 s intervals. Therefore, the overall quality and availability of the data, for the purpose of this MVD is considered acceptable ("Data quality/availability" rating = 3).

Overall, the HF test series is rated at 2.6, which is below the "acceptable" threshold. The main negative of the HF trials is the very low concentration measurements, which are well below the typical range of LFL values (1-5%) for flammable dispersion scenarios. Given the availability of higher rated test series that fit the same categories, the Porton trials are not included in the flammable dispersion MVD.

2.20 Thorney Island

Experimental campaign	Thorney Island (TI)
Test dates:	1984
Test location:	Thorney Island, UK
Number of tests:	26
Tests performed by:	UK Health and Safety Executive and National Maritime Institute
Brief description:	Low momentum releases of Freon 12/nitrogen mixture.
References:	Stewart et al., 2016 [3] McQuaid and Roebuck [2] McQuaid [3]
Data confidentiality:	Open (based on publicly available data)
Model validation category	
Material:	Freon 12/nitrogen mixture
Release Type:	Low momentum gas
Dispersion Area:	Unobstructed
Test series rating	
Overall:	**2.6**
Relevance:	3
Material:	1
Scale:	4
Repeatability:	2
Data Quality/Availability:	3

2.20.1 Description

The Thorney Island test series took place at a former Royal Air Force station at Thorney Island, in the United Kingdom. The tests consisted of low-momentum releases of a Freon 12/Nitrogen mixture. The vapor clouds dispersed over mostly flat terrain. Figure 2-24 shows a schematic of the release area and measurement array.

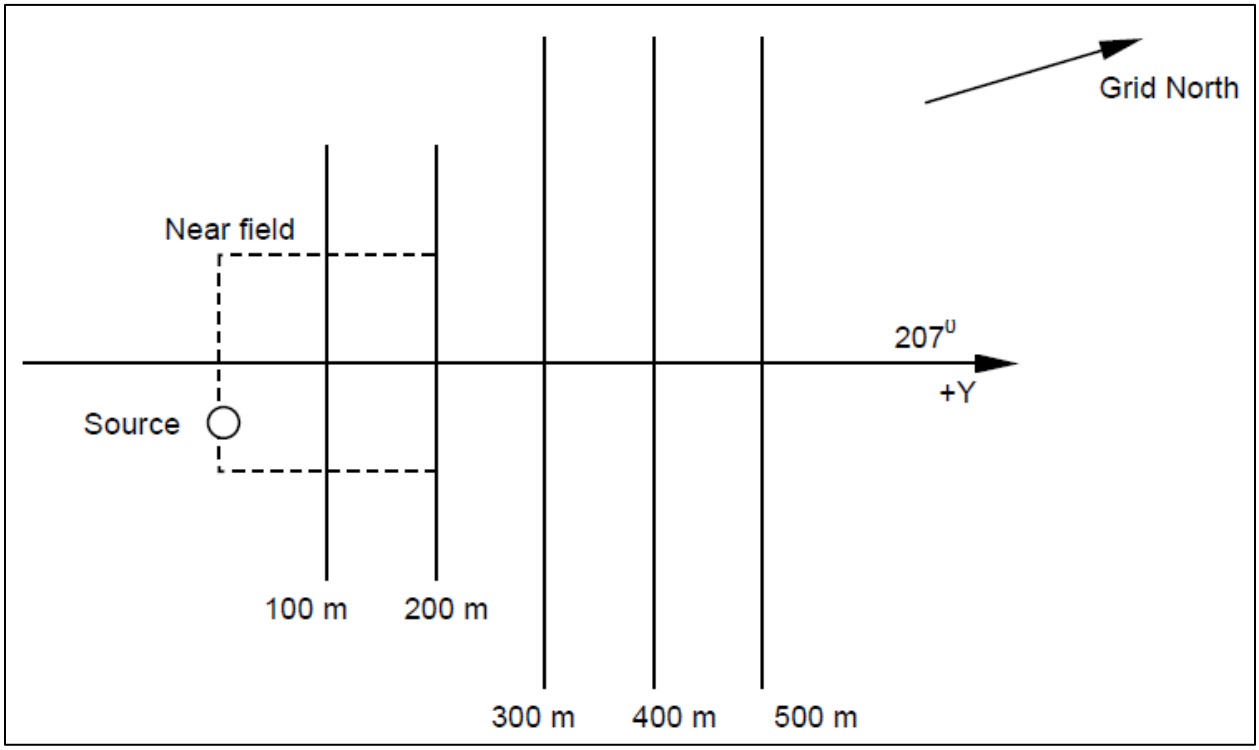

Figure 2-24. Thorney Island release area and measurement array [3].

2.20.2 Test Series Grouping and Rating

The Thorney Island trials consisted of releases of a mixture of Freon 12 and nitrogen. In some of the trials, the gas mixture was held at atmospheric pressure and temperature in a tall cylindrical container, whose side walls were suddenly released, allowing the dense gas to slump to the ground and disperse. In other trials, the mixture was introduced upwards from the ground and impinged onto the bottom side of a horizontal plate, thus spreading radially. In both cases, the gas cloud then dispersed over flat terrain, with no obstructions. The test series therefore fits in the following categories:

- Material: Non-flammable
- Release Type: Low momentum
- Dispersion Area: Unobstructed

The dispersion of low-momentum dense clouds is a frequently modeled scenario, albeit from different source configurations than those tested at Thorney Island ("Relevance" rating = 3). Mixtures of Freon 12 and nitrogen are not used in LNG facilities ("Material" rating = 1). The dimensions of the cloud as well as the dispersion measurement area are consistent with typical studies ("Scale" rating = 4).

In every field scale test series, replicating the same test conditions (including the weather) is extremely difficult, therefore, the repeatability of field scale experiments is inherently limited ("Repeatability" rating = 2). The overall quality and availability of data from the Thorney Island trials is considered acceptable for the purpose of this MVD ("Data quality/availability" rating = 3).

Overall, the Thorney Island series is rated at 2.6, which is below the "acceptable" threshold. Given the availability of higher rated test series that fit the same categories, the Thorney Island trials are not included in the flammable dispersion MVD.

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