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A CONCEPTUAL MODEL FOR CHARACTERIZING HUMAN AND ASSET RISK FROM UNCONTROLLED GAS RELEASES

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The unintentional release of pressurized gases poses a significant safety concern in industrial environments, with the potential to harm personnel, damage equipment, and disrupt operations. This work outlines a general modelling approach used to evaluate and display the potential consequences of such events. The focus is on how the physical release behaviour, thermal effects, and atmospheric transport can be combined to estimate hazard zones. The framework draws on mathematical and engineering principles to approximate release intensity, the potential for heat exposure following ignition, and the movement of gas in the surrounding environment under varying meteorological conditions. These outputs support the definition of indicative ranges associated with different levels of human harm and asset impact, enabling the visualisation of spatial envelopes of concern. Although simplified relative to high-fidelity computational simulations, the approach is designed to provide timely insight into likely consequence footprints, supporting scenario comparisons, emergency planning, and preliminary risk assessment activities. Its flexibility allows for adaptation to different gas compositions, site layouts, and operating contexts, making it suitable for use across a range of industrial applications. More broadly, the work demonstrates how integrating physical release theory with atmospheric dispersion concepts can offer a practical way to understand potential impacts and guide protection or mitigation decisions.

Keywords: Consequence modelling, Thermal radiation, Jet fire, Hazard zoning.

1. Introduction

In the oil and gas industry, the accidental release of pressurised hydrocarbons can result in severe damage to physical assets, environmental systems, and human life. Failures may occur in pipelines, valves, flanges, or wellhead assemblies, leading to the uncontrolled release of high-pressure substances contained within these systems. Following a rupture, hazardous gas clouds may form in the immediate vicinity of the release point and can subsequently result in jet fires, flash fires, or vapour cloud explosions.

By understanding the mechanisms and characteristics of these potential events, it becomes possible to implement preventative measures and to minimise the likelihood and severity of catastrophic outcomes. Improvements in emergency response planning, safety equipment, site layout, and operational procedures can significantly reduce the impact of accidental releases. Most importantly, a robust preliminary risk-screening process can be established to identify high-risk scenarios at an early stage of design or operation.

A variety of consequence-analysis tools are currently employed across the industry to evaluate the potential impacts of such releases. These tools typically rely on complex thermodynamic calculations, computational fluid dynamics, and specialised commercial software platforms, which are often resource-intensive in terms of computation time, expertise, and cost Saturnino Lorenza and Eulalia (2025). The conceptual model proposed in this study integrates gas-release theory, Gaussian atmospheric dispersion modelling, and jet-fire thermal radiation modelling into a unified framework. This combined tool set enables rapid, indicative consequence assessment and provides a practical platform for early-stage risk screening and decision support.

2. Model Conceptual Framework

To establish the conceptual framework, three physical sub-models are integrated into a single model for characterising human and asset risk associated with uncontrolled gas releases. The first sub-model is based on choked-flow theory to estimate the mass flow rate following a rupture, reflecting the typical oil and gas industry scenario in which high-pressure systems depressurise rapidly into a low-pressure environment. The second sub-model employs a Gaussian plume formulation to describe the atmospheric dispersion of the released gas. In the event of spontaneous ignition, the third sub-model evaluates jet-fire thermal radiation using established radiation correlations and associated damage criteria.

The combined outputs of these sub-models are presented as concentration and radiation contours over a two-dimensional spatial grid, enabling intuitive visual interpretation of the potential consequences of a rupture event. Additional data-driven graphical overlays are incorporated to support further interrogation of the results and to enhance understanding of the predicted human and asset impact zones.

3. Gas Release Modelling

In the oil and gas industry, reservoir fluids exhibit significant variability in composition, primarily as a result of the geological history and transformation of organic material at the reservoir location. The four principal reservoir fluid types encountered are natural gas, crude oil, heavy oil, and tar-sand bitumen Speight and G. (2017). This study focuses on natural gas releases, as these are common in high-pressure production and transmission systems and are particularly prone to choked-flow discharge following loss of containment.

Natural gas compositions vary widely; however, the dominant components typically include methane, with varying concentrations of nitrogen, carbon dioxide, hydrogen sulphide, and higher hydrocarbons such as ethane. The present conceptual model considers a representative natural gas mixture consisting of nitrogen (N_2), methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S), and ethane (C_2H_6). The framework is flexible and allows for extension to include additional species as required for specific reservoir conditions.

3.1. *Gas Mixture Properties*

To initiate the gas release calculations, key thermodynamic properties of the mixture are required. These include the molar mass, molar specific heat capacity at constant pressure, and mole fraction of each component. The mixture properties are evaluated using mole-fraction-weighted averages to determine the effective molecular weight and specific heat of the combined fluid.

Table 1 summarises the representative composition and thermochemical properties used in the present model.

Table 1. Gas mixture properties

Element	Molar Mass (g/mol)	Specific Heat (J/mol.K)	Mole Fraction (%)
N_2	28.01	29.1	1
CH_4	16.04	35.7	85
CO_2	44.01	37.1	3
H_2S	34.08	34.6	1
C_2H_6	30.07	52.5	10

3.2. *Choked Flow Mass Release*

With the possibility of a potential rupture within the various systems, pipelines, and associated equipment, the release must be conceptually and visually represented in order to illustrate the potential risks that such an event may pose. To initiate this conceptualisation process, basic mathematical calculations are required to determine the potential mass flow rate of a leak, which is subsequently used to evaluate dispersion behaviour and jet-fire consequences.

As these systems typically operate at elevated pressures, a sudden rupture will result in rapid depressurisation to atmospheric conditions. During this de-pressurisation, the gas velocity at the point of fracture can reach sonic conditions. Under such circumstances the flow becomes independent of downstream pressure and the release is therefore characterised as choked flow.

By applying choked-flow theory, a physically justified and conservative estimate of the maximum achievable mass flow rate is obtained. This estimate is essential for consequence analysis and provides a robust basis for further model development and improvement. The mass flow rate is calculated using the following expression:

$$\dot{m} = C_d \, A \, P_0 \sqrt{\frac{\gamma}{RT_0} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

$\dot{m}$ = mass flow rate (kg s^{-1})

C_d = discharge coefficient (-)

A = effective rupture area (m^2)

P_0 = upstream stagnation pressure (Pa)

T_0 = upstream stagnation temperature (K)

γ = ratio of specific heats (c_p/c_v) (-)

R = mixture specific gas constant (J kg^{-1} K^{-1})

4. Gas Dispersion Modelling Approach

In the event of a potential gas leak in the oil and gas industry, whether from a pipeline or wellhead, a visual representation of the affected region is essential. Estimating the spatial extent of a gas release allows emergency responders and disaster management teams to plan mitigation strategies, establish safety zones, and minimize environmental and ecological damage. Gas dispersion modelling, therefore, serves as a critical tool for both preventive risk assessment and emergency response planning.

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \Bigg[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \Bigg] \tag{2}$$

$C(x, y, z)$ = Gas concentration (kg m^{-3})
Q = Mass release rate (kg s^{-1})
u = Wind speed at release height (m s^{-1})
σ_y = Lateral dispersion coefficient (m)
σ_z = Vertical dispersion coefficient (m)
H = Effective release height (m)

The modelling approach adopted in this study is based on the Gaussian atmospheric dispersion formulation (see Equation 2), which provides a mathematically robust framework for estimating pollutant transport in the atmosphere. The Gaussian model was developed through the work of Pasquill and Gifford in the 1960s as a semi-empirical solution describing the dispersion of airborne pollutants under different atmospheric turbulence conditionsSnoun et al. (2023). These formulations are widely applied to both puff and plume representations of pollutant releases. In this conceptual assessment, the Gaussian plume model is employed.

For simplification of the conceptual model, the following assumptions are made:

(1) The released gas mixture consists of five primary components.
(2) Wind speed is assumed constant over the

modelling domain.

(3) Rapid atmospheric or meteorological fluctuations are neglected.

(4) The gas release rate is steady and continuous.

Under these assumptions, atmospheric stability becomes the primary factor governing plume dispersion. The Gaussian plume model incorporates atmospheric stability through the vertical and horizontal dispersion coefficients (σ_y and σ_z). Stability conditions are classified according to the Pasquill–Gifford scheme, which defines six stability categories describing turbulence intensity in the atmosphere. These categories, summarized in Tables 2 and 3, provide a general description of the meteorological conditions and their influence on pollutant dispersion behaviour.

Table 2. Atmospheric stability classes and typical meteorological conditions

Class	Category	Typical Conditions
A	Very Unstable	Strong solar radiation, clear skies, low wind speeds
B	Unstable	Moderate solar radiation, light winds
C	Slightly Unstable	Weak solar radiation or moderate winds
D	Neutral	Overcast skies or strong winds (day or night)
E	Stable	Night-time, partial cloud cover, light winds
F	Very Stable	Clear night, calm winds, strong surface cooling

5. Jet Fire Modelling

In the event of immediate ignition following a pressurised natural gas release, a jet fire may develop at the rupture location. Jet fires are characterised by high-momentum flames and intense localised thermal radiation, which pose severe risks to personnel and equipment. Within the present conceptual framework, jet fire consequences are estimated using a screening-level radiation model consistent with the methodology presented by Tong et al. Tong et al. (2013).

Table 3. Dispersion characteristics by atmospheric stability class

Class	Dispersion Behaviour
A	Very strong turbulence; rapid vertical and horizontal plume spread
B	Strong turbulence; significant plume growth
C	Moderate turbulence; steady dispersion
D	Mechanical turbulence dominates; average dispersion
E	Weak turbulence; reduced vertical mixing
F	Very weak turbulence; minimal vertical spread and narrow plume

The combustion power released by the jet is calculated from the mass discharge rate obtained from the choked-flow model:

$$\dot{Q} = \eta\, \dot{m}\, H_c \tag{3}$$

$\dot{Q}$ Total combustion heat release rate (W)
η Combustion efficiency factor (-)
$\dot{m}$ Mass flow rate ($\mathrm{kg\,s^{-1}}$)
H_c Heat of combustion of the gas ($\mathrm{J\,kg^{-1}}$)

A fraction of this energy is emitted as thermal radiation. The radiative heat flux at a distance r from the jet is determined using a point-source radiation approximation:

$$I(r) = \frac{\chi\, \dot{Q}}{4\pi r^2} \tag{4}$$

$I(r)$ Thermal radiation intensity ($\mathrm{W\,m^{-2}}$)
χ Radiative fraction (-)
r Distance from the jet origin (m)

This approach provides a computationally efficient method for estimating thermal hazard zones and is appropriate for early-stage consequence screening.

6. Thermal Harm and Damage Criteria

To translate radiation levels into consequence zones, thermal radiation thresholds for harm to personnel and damage to equipment are applied. The criteria adopted in this work are based on the jet-fire consequence evaluation study of Tong et al. Tong et al. (2013), which presents experimentally supported radiation thresholds.

Table 4. Thermal harm criteria for personnel Tong et al. (2013)

Heat Flux (kW m^{-2})	Effect on Personnel
6.5	Fatality likely
4.3	Serious injury
1.9	Minor injury

Table 5. Thermal damage criteria for equipment Tong et al. (2013)

Heat Flux (kW m^{-2})	Effect on Equipment
100	Equipment totally destroyed
35	Equipment seriously damaged
25	Structural components deformed

These thresholds enable the conversion of calculated radiation intensity fields into hazard contours for visual risk representation.

7. Data Visualisation and Interpretation

To facilitate practical interpretation of the modelling outputs, both gas dispersion and jet fire radiation results are converted into spatial visualisations. These plots transform mathematical model predictions into hazard envelopes that support rapid risk screening and emergency planning.

7.1. *Jet Fire Radiation Visualisation*

Thermal radiation from the jet fire model is calculated using a point-source radiation formulation and visualised in three complementary ways.

Radiation–Distance Profile (Fig. 1). Radiation intensity is plotted against radial distance from the leak location. The curve illustrates the inverse-square decay of thermal radiation and provides a direct method for estimating safe separation distances.

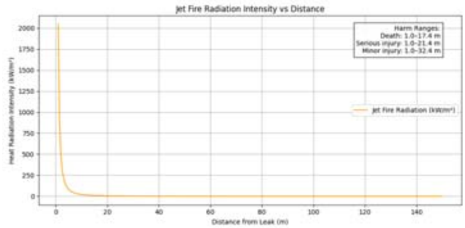

Fig. 1. Jet fire radiation intensity as a function of distance from the leak source.

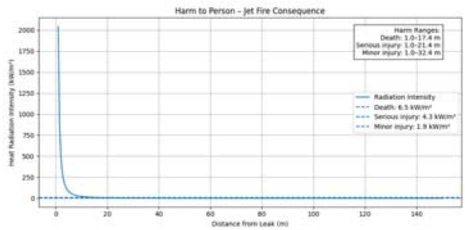

Fig. 2. Radiation profile with harm-to-person thresholds and resulting consequence ranges.

Harm-to-Person Consequence Zones (Fig. 2). Human injury zones are determined by superimposing radiation thresholds onto the radiation–distance curve. Intersections between the model prediction and harm criteria define ranges associated with minor injury, serious injury, and fatality risk.

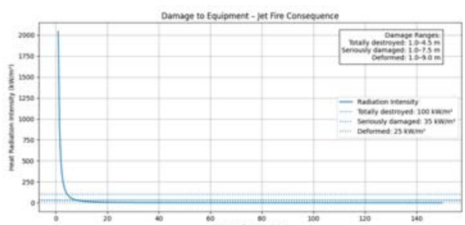

Fig. 3. Radiation profile with equipment damage thresholds.

Equipment Damage Consequence Zones (Fig. 3). Thermal radiation thresholds for equipment damage are applied in the same manner to identify distances at which deformation, serious damage, or total destruction may occur.

Fig. 4. Two-dimensional jet fire radiation contour overlaid on the site map, showing spatial thermal hazard zones.

Two-Dimensional Radiation Envelope (Fig. 4).
A Cartesian grid surrounding the release point is evaluated, and contours of equal radiation intensity are plotted to produce a thermal hazard envelope. This representation provides a spatial view of impact zones and can be superimposed onto site layouts.

7.2. *Gas Dispersion Visualisation*

Gas concentration fields from the Gaussian plume model are visualised as contour maps to represent the extent of the gas cloud.

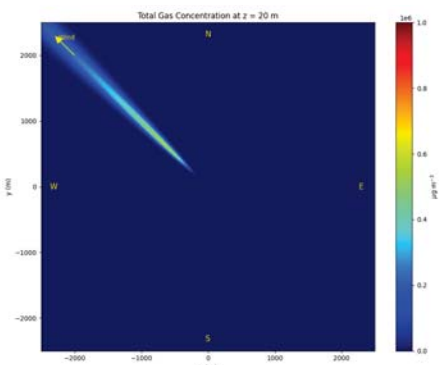

Fig. 5. Total gas concentration field at $z = 20$ m showing plume dispersion.

Total Gas Concentration Field (Fig. 5).
The combined concentration of all gas species is displayed over a two-dimensional grid, illustrating the spatial extent of the hazardous or flammable gas cloud.

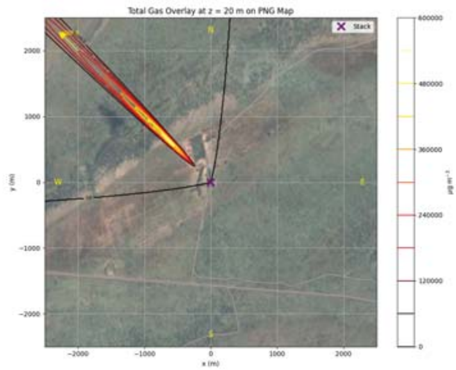

Fig. 6. Gas concentration contours overlaid on site map for spatial interpretation.

Site Overlay Representation (Fig. 6).
Dispersion contours are superimposed onto site imagery to enable direct interpretation of affected areas relative to physical infrastructure.

7.3. *Integrated Interpretation*

Figures 1–6 collectively provide a comprehensive spatial representation of potential accident consequences:

- Dispersion maps indicate regions where hazardous gas concentrations may exist prior to ignition.
- Radiation envelopes indicate thermal impact zones in the event of immediate ignition.

Together, these visualisations support the identification of evacuation zones, equipment vulnerability regions, passive fire protection requirements, and safe emergency response positioning.

8. Computational Performance and Future Acceleration

Although the individual sub-models used in this conceptual framework rely on simplified physical formulations, the integrated approach can become computationally demanding when applied to fine spatial grids, multiple meteorological conditions, or large parametric studies. The Gaussian dispersion and radiation models require repeated evaluation of mathematical expressions over two-dimensional domains, and this cost increases further when generating contour fields for visualisation and decision support. Under conventional serial CPU execution, the framework is suitable for single-scenario screening but becomes resource-intensive when used for batch analyses, sensitivity studies, or near-real-time applications.

To improve scalability, future development will explore parallel computing approaches, particularly graphics processing unit (GPU) acceleration. The grid-based, independent nature of the dispersion and radiation calculations makes them well-suited to parallel execution, enabling thousands of operations to be performed simultaneously. Migrating numerical routines to GPU platforms (e.g., CUDA or OpenCL) could significantly reduce computation time, enabling rapid multi-scenario evaluation and enhanced real-time hazard visualisation. This enhancement represents an implementation-level improvement and does not alter the conceptual structure of the framework, but strengthens its applicability to modern engineering risk assessment work flows.

9. Results and Discussion

The integrated modelling framework produces both gas dispersion and jet fire radiation outputs, which are visualised as spatial hazard envelopes. These visualisations translate mathematical model results into intuitive representations that support engineering judgement, emergency planning, and risk screening.

9.1. *Gas Dispersion Behaviour*

The time-averaged total gas concentration field at 20 m elevation is shown in Figure 5. The plume exhibits the expected Gaussian dispersion structure, characterised by a narrow high-concentration core near the release location and progressive lateral and vertical spreading downwind. The plume centreline aligns with the prevailing wind direction, confirming the dominant role of meteorological conditions in determining the transport of the released gas.

Regions of elevated concentration indicate potential flammability and toxic exposure zones prior to ignition. The rapid reduction in concentration away from the centreline demonstrates the diluting effect of atmospheric turbulence, particularly under the selected stability conditions.

Overlaying the dispersion contours onto the site layout (Figure 6) provides a practical interpretation of the hazard footprint. This representation identifies infrastructure, access routes, and surrounding areas that intersect with the predicted gas cloud. Such spatial information is valuable for defining temporary exclusion zones, planning evacuation routes, and positioning emergency response resources.

9.2. *Jet Fire Radiation Characteristics*

The jet fire radiation intensity as a function of distance from the release point is presented in Figure 1. The steep decay of radiation with increasing distance follows the inverse-square relationship expected for point-source radiation. Extremely high thermal loads are confined to the near-field region, while radiation intensity decreases rapidly beyond several meters from the source.

Figures 2 and 3 translate these radiation levels into practical consequence zones. The personnel harm plot shows the distances associated with minor injury, serious injury, and fatality likelihood. Similarly, the equipment damage plot identifies regions where structural deformation, severe damage, or total equipment failure may occur. These threshold-based interpretations provide clear safety separation distances that can inform layout design, barrier placement, and passive fire protection strategies.

9.3. *Combined Consequence Interpretation*

The dispersion and jet fire results represent two stages of the same hazard scenario:

- The **dispersion maps** describe the pre-ignition hazard, defining where a flammable or toxic gas cloud may exist.
- The **radiation plots** describe the post-ignition hazard, defining zones of thermal exposure where ignition should occur.

Together, these outputs provide a comprehensive spatial representation of risk. The plume footprint identifies areas requiring gas detection, ventilation, and evacuation planning, while the radiation contours define thermal exclusion zones and equipment vulnerability regions. The combination of these results supports decision-making related to emergency response positioning, personnel safety management, and asset protection.

9.4. *Computational Performance Considerations*

Although the individual sub-models rely on simplified physical formulations, the integrated framework can become computationally demanding when applied to fine spatial grids, multiple meteorological conditions, or large parametric studies. The Gaussian dispersion and radiation calculations require repeated evaluation of mathematical expressions across two-dimensional domains, and the cost increases further when generating contour fields for visualisation and decision support. Under conventional serial CPU execution, the framework remains efficient for single-scenario screening but becomes resource-intensive for batch analyses, sensitivity studies, or near-real-time applications.

To improve scalability, future development will explore parallel computing approaches, particularly graphics processing unit (GPU) acceleration. The grid-based and independent structure of the dispersion and radiation models makes them well-suited to parallel execution, where large numbers of grid points can be processed simultaneously. Migrating numerical routines to GPU platforms could significantly reduce computation times, enabling rapid multi-scenario evaluation and enhanced real-time hazard visualisation. This enhancement represents an implementation-level improvement and does not alter the conceptual structure of the framework, but strengthens its applicability to modern engineering risk assessment workflows.

9.5. *Model Applicability and Limitations*

The modelling approach provides rapid, computationally efficient estimates of consequence footprints suitable for conceptual design and preliminary risk assessment. While the Gaussian plume and point-source radiation assumptions simplify real physical processes, they capture the dominant transport and heat transfer mechanisms and produce conservative hazard estimates appropriate for screening purposes.

High-fidelity simulations could refine these predictions by incorporating complex terrain effects, transient meteorological variations, and detailed flame geometry. Nevertheless, the present framework offers a practical balance between physical realism and computational efficiency, enabling rapid evaluation of multiple scenarios and supporting early-stage safety decision-making.

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