A risk-based approach to safety distance determination in the process industry

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Safety distance determination is a key design issue in the process industry. This is usually carried out early in the project lifecycle and often represents a "point of no return" in design development. This may have a dramatic impact on a project, either because some serious safety issues may emerge later or because a poor selection of safety distance can prevent optimum utilisation of available space. Full understanding of safety distances is typically only achieved when it is too late to implement without significant changes. For the layout of plant, prescriptive distances between equipment items are generally used, according to a tabular matrix including standard spacing distances. These values have been based on empirical or statistical data and as such are not risk-based. Foster Wheeler has implemented a risk-based methodology for the determination of safety distances in the process industry, which encompasses all major hazard scenarios including jet fires, flash fires, explosions, boiling liquid expanding vapour explosion (BLEVE), and toxic releases. This methodology incorporates the fundamental criteria of the parts count procedure to identify the most critical risks, along with representative streams and substances, with the aim of providing a simple but effective tool to be used early in the project lifecycle, identifying and taking into account the process parameters and the associated uncertainty. Modelling has been calibrated using DNV PHAST 6.6 to verify the validity of the results obtained. Some specific case studies are included in this article.

Keywords: safety distances, spacing, siting, inherently safer design.

Introduction

On Saturday July 9, 1976 one kg of 2,3,7,8 tetrachlorodibenzodioxin (TCDD) was released through a rupture disk at ICMESA plant in Seveso, Italy (Homberger et al., 1979). That was not only the day when the world faced for the first time the hazard of a toxic cloud potentially spreading over the whole community, but it was also the beginning of a huge change in regulatory and methodological approach to process safety. Seveso directives I (1982), II (1997) and III (2012), have introduced the concept of risk in the industry and have addressed the quantitative risk assessment (QRA) approach for siting of potentially hazardous installations. Previously, a prescriptive approach was the general method used to manage safety and occupational aspects of the industrial world. The methodological change was progressively reflected in all of the safety and occupational health laws of the European Union. Through the *New Approach and Global Approach*, the European Commission (2000) introduced also the individual responsibility for the site owner to provably certify the acceptability of risk. In the industrial sectors potentially affected by major hazards, such as the oil and gas and petrochemical/chemical industries, this process has been implemented relatively more quickly than in others, due to the cultural background and to the high hazards. The necessity to minimize risk and a progressively growing consciousness about *friendly safety* (Kletz, 2010) have led to the adoption of techniques and methodologies which are capable of reducing post-incident measures and able to develop increasingly sustainable approaches because of their inherent low hazard and potential for harm. The key concept of "Inherent safety", which had been introduced several years earlier by Kletz, (Kletz, 2010) is the *Limitation of effects by changing designs or reaction conditions rather than by adding protective equipment that may fail or be neglected*. QRA studies in the industry have traditionally been implemented as a separate stand-alone task, often not synchronized with the design development. A possible outcome of this for the design team is to be delayed while implementing suitable design and layout changes, which generally results in a significant addition of protective measures, a non-harmonized approach, a very significant impact on project cost and, last but not least, an ineffective achievement of the safety targets. This is often the case with plant/equipment siting. The traditional approach consists essentially of the adoption of prescriptive distances, which may in fact be unsafe, or which may lead to the available space being used in a less than optimized manner. Foster Wheeler's experience includes a long project execution history, throughout which the necessity to develop risk-based simplified techniques to identify safety distances between the plant units, between main equipment and to occupied areas, has increased in importance. This article describes this evolution and presents a state-of-the-art quantitative risk assessment approach to safety distance determination

Background of the methodology of the separation distance assignment

Early guidance about safety distances was given by Armistead (1952), House (1969), Backurst and Harker (1973), Kaura (1980) and Anderson (1982). In 1976, the Dow Chemical company included safety distances in their Fire and Explosion Index (FEI) Guide. Developed in the Eighties, The Mond Fire Explosion and Toxicity Index method developed by Lewis (1970) is an extension of the original Dow Index method. Exxon (1998) issued some safety design standards which specified prescriptive values for lay-out spacing. Similar separation distance tables have been given by Mecklenburgh (1985) and Industrial Risk Insurers (1991). Mecklenburgh also carried out a categorisation of the most important hazardous scenarios to be used in support of plant layout. Prescriptive separation distances for small and large tanks containing flammable liquids have been given by the Health and Safety Executive in 1998 and, for LPG, in 2013. The U.S.'s Center for Chemical Process Safety (CCPS) (2003) has provided typical separation distances between various elements in open-air process facilities. These tables are based on historical and current data from refining, petrochemical, chemical, and insurance sectors. The data were developed based on experience and engineering judgment and, as clearly stated in the CCPS textbook, *not always on calculations.* On the other hand, risk- and consequence- based methods have increased their importance and this has been progressively reflected in code and standards. In 1996 the International Atomic Energy Agency (IAEA) (Van den Brand et al) released a comprehensive paper dealing with risks to public health from fires, explosions and releases of toxic substances outside the boundaries of hazardous installations due to major accidents in fixed installations with off-site consequences; maximum distances and areas of effect are given on the basis of the classification of substances by effect categories. The IAEA (1999) has also issued a specific paper on safety distances relative to hydrogen according to effects analysis. API 521 (2008) provides guidance for predicting the distance to flammable concentration limit following a gas momentum-driven release; this formula has been reviewed recently by Benintendi (2010) as a more accurate approach to identify hazardous areas. The same standard includes a method to determine flame radiation to a point of interest, using Hajek and Ludwig's formula (1960). The European Industrial Gases Association report *Determination of safety distances* (2007) provides the basic principles for calculating appropriate safety distances for the industrial gas industry. The well-known U.S. Environmental Protection Agency Risk Management Program Guidance for Offsite Consequence Analysis (2009) provides guidance on how to conduct the offsite consequence analyses for Risk Management Programs required under the Clean Air Act. This guidance identifies distances to specific toxic, flammable and overpressure endpoints, based on the substance characteristics and on release models. Also Factory Mutual (2012) states the necessity of identifying separation distances accounting for specific hazard factors and provides some quantitative graphs for outdoor chemical processing equipment. Finally, ATEX Directive 1999/92/EC (2000) requires hazardous area classification, which consists of the sizing of areas where explosive atmospheres can exist, which is indirectly a safety distance assessment. The Hazardous area classification primary standard is BS-EN-60079-10-1 (2009), which, for gases and mists, is based on the calculation models provided by Cox, Lee and Ang (1993), Iving et al (2008), Ballal and Lefebvre (1982).

Safety distances as a part of inherently safer design

Safety distance identification through a risk-based methodology is considered to be a part of the inherently safer design philosophy. In 1990 Englund developed a section of his Chemical Hazard Engineering Guidelines dealing with separation distances within the inherently safer design procedure. In a recent book, *Process Plants: A Handbook for Inherently Safer Design*, (2010), Trevor Kletz has said: "*The essence of the inherently safer approach to plant design is the avoidance of hazards rather than their control by added-on protective equipment"*. Properly assessing the outcome of an incident scenario, conservatively identifying its extent and, finally, accounting for these data to arrange plant lay-out, minimizing in this way the likelihood of any impact, can be considered consistent with Kletz's statement. His inherent safety approach includes the following elements, to be addressed early in a project phase:

1. intensification or minimization
2. substitution
3. attenuation or moderation
4. limitation of effects

If one prevents the worst-case outcome or impact of an incident, and implements this prevention early in the design, one has worked according to Kletz's philosophy. This is essentially Foster Wheeler's approach in preliminary safety distance assessment. In addition to designing a *friendlier plant*, another Kletz definition, this allows one to optimize the space resources with positive impact on the project cost and plant operability.

Foster Wheeler' Safety Distance Approach

Foster Wheeler utilizes DNV PHAST 6.7 to carry out consequence assessment in safety studies. Early in 2012, Foster Wheeler decided to develop a simple calculation method to assess safety distances to be used for preliminary spacing of main equipment and buildings. A first approach (Saetta, 2012) was developed, based on models and inputs provided by CCPS (2000),(2003), TNO (2005), Crowl, and Louvar (2002), Cox, Lees and Ang (1990), and Nelson (1969), which were tailored to the most representative design scenarios of oil and gas and energy sectors. In 2013 Angela Rodriguez Guio, a Foster Wheeler process safety engineer, within her dissertation for the degree of Master of Science in Process Safety and Loss Prevention at the University of Sheffield, developed and integrated Saetta's approach and provided a more comprehensive picture of the method. Unlike the software used for consequence assessment, Guio's approach systemically integrates the hazards and consequences scenario within a holistic framework aiming at providing results strictly related to the scope of work. Accordingly, the following specific aspects have been implemented in approach:

- representative equipment and streams, consisting of the most significant plant items and chemical releases, based on Foster Wheeler's project execution experience, have been identified
- parts count methodology has been considered to identify deterministic and probabilistic significance of impact events
- a specific procedure has been defined, consisting of the following basic steps:

- design data and document collection and analysis, including preliminary plot plans, process flowsheets, block flow diagram,hazardous materials table, equipment list
- parts count analysis and release/impact models
- thermal, toxic and explosions models
- identification of safety distances
- sensitivity analysis

A broad comparison with DNV PHAST simulation data has been carried out, which has shown a satisfactory representation of the investigated scenarios.

Foster Wheeler's FEATHER™ Model

FEATHER™ (**F**ire, **E**xplosion **a**nd **T**oxicity **H**azard **E**ffect **R**eview) is a software program developed by Foster Wheeler aimed at automatically identifying the hazard scenarios and providing frequency and safety distances, along with iso-contour diagrams. Safety distances are defined as the distance from the release or blasting (BLEVE) source to a pre-defined toxic, flammable, heat-radiation, overpressure endpoint. This software has been programmed in Microsoft Visual Basic and incorporates a physical-chemical database (API, 2006), (Perry and Green, 2008) and toxicological date base (NIOSH, OSHA). FEATHER steps have been illustrated in Figure 4, where the light grey boxes represent input data and the dark grey boxes represent the output data or intermediate data automatically calculated or uploaded by the software.

Chemical substances

Hydrocarbons from methane to octane, crude oil (Nelson, 1969), hydrogen, carbon dioxide, ammonia are covered, along with the corresponding hazard scenarios.

Flow Models

Choked/non-choked all-gas flows are calculated according to adiabatic outflow formulas. Two-phase flows are described, assuming liquid state at the outlet because the Fauske and Epstein critical length (1988) for phase transition is not exceeded. All-liquid-flow is calculated through Torricelli's formula.

Dispersion

Dispersion modelling has been approached by tuning a blending of sequential models, taking into account the initial jet momentum/air entrainment in the near field (Benintendi, 2010), the fluid molecular weight in the medium field (Britter and McQuaid), and the Gaussian behaviour in the far field. Wind and Pasquill weather categories data are selected by the user.

Pool evaporation and stripping

The MacKay & Matsugu (Kawamura, 1987) formula has been adopted because of its validation against experiments. For crude oil, gasolines, diesels and kerosenes, the Reid Vapour Pressure can be used to estimate the mass of vapour evaporating from the liquid using the method described by Nelson (1969). It has been assumed that all of the toxic gas is stripped from the liquid in order to be conservative. Once this mass of toxic vapour is known, dispersion models have been applied.

Hazard scenarios

Hazard scenarios are automatically identified by the software, based on the characteristics of the substances.

Pool fire

Both diked and undiked pool fires have been modelled. The evaporation effect has been considered according to the methodology outlined above. The TNO (2005) model has been adopted.

Jet fire

Flame dimensions and the radiative flux calculation have been modelled, according to TNO (2005). A light or sooty flame option can be selected.

Flash fire and toxic release

Flash fire has been modelled considering the distance to substance Lower Explosive Limits. This is conservative and reasonable. Therefore, toxic release has been modelled in the same way, just replacing the specific endpoint.

Open space explosion

The TNT method has been selected for modelling open space explosion. Despite the claimed poor accuracy stated in the literature, comparison with DNV PHAST has shown very good results.

Congested space explosion

Explosion in congested space (module and units) has been modelled according to the method provided by Puttock (1995, 1999, 2001). The user is requested to provide geometrical and congestion data. The software automatically calculates whether a flammable atmosphere reaches the module/unit and assumes that explosion occurs inside, which is a reasonable and conservative hypothesis.

BLEVE

BLEVE has been modelled according to the method provided by CCPS (2000).

FEATHER accuracy and validity

FEATHER works according to the exceedance criterion for identifying significant hazard scenarios. Typically a frequency of 10^{-4}/yr is assumed as the exceedance limit, which can be changed. Accordingly, a dual option has been implemented, which allows for the provision of the iso-contours for the significant scenarios only, or for all of the possible incidents. The software findings have been compared with DNV PHAST results. Some examples have been included in Figures 1, 2 and 3, showing the calculation of distances to acceptable radiation levels for propane jet fires of differing pressures, heptane pool fires of differing pool diameters and fireballs of differing initial flammable masses. The comparability is also very good within the sensitivity analysis results. The software is not intended to replace validated software adopted in QRA and consequence assessment studies. Nevertheless, it can be considered a useful and flexible tool for verification of initial equipment spacing.

Conclusion

Foster Wheeler is implementing a risk-based approach to safety distance determination early in the design of process plant. Spacing of equipment and separation distance identification is a major issue which has been traditionally approached by means of prescriptive distances, based on statistical data. A specific risk-based methodology has been used and software has been developed, which includes and integrates validated models and provides satisfactory predictive results in terms of frequency and safety distances. The method is considered a step forward in the implementation of inherently safer design.

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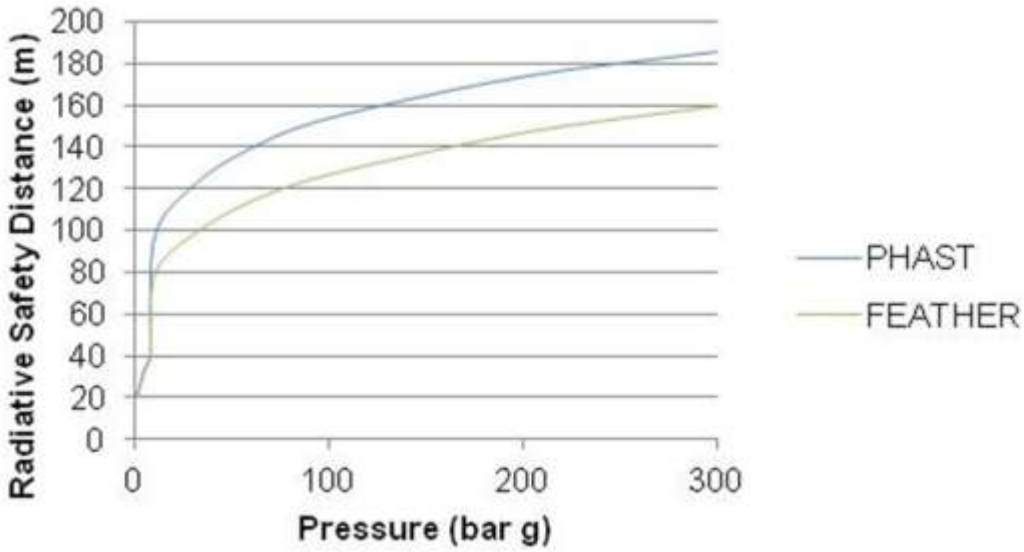

Fig. 1 – Propane jet fire. Comparison of FEATHER vs PHAST

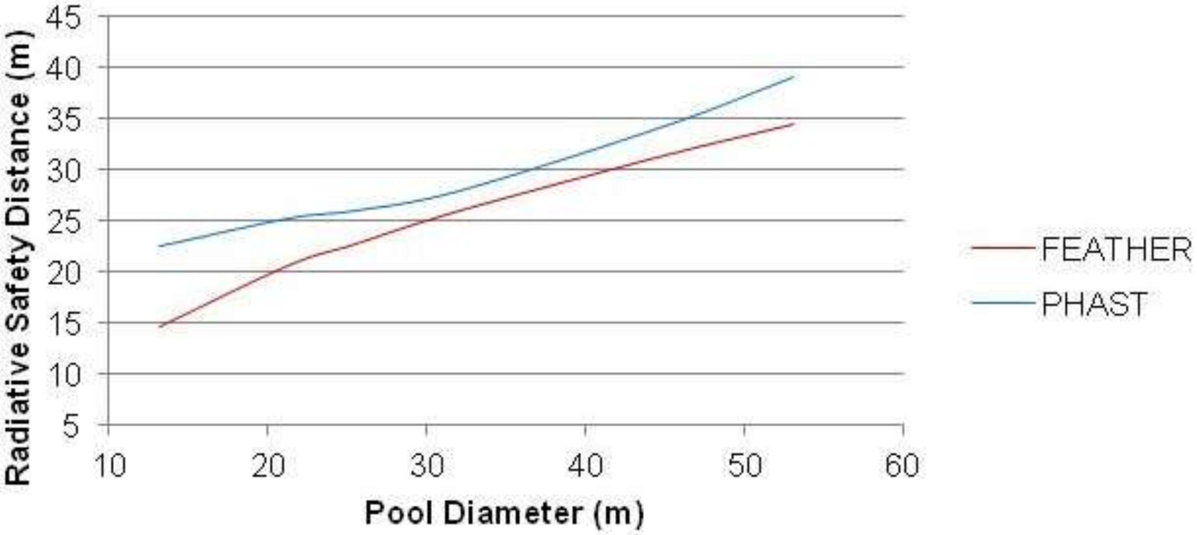

Fig. 2 – Heptane pool fire. Comparison of FEATHER vs PHAST

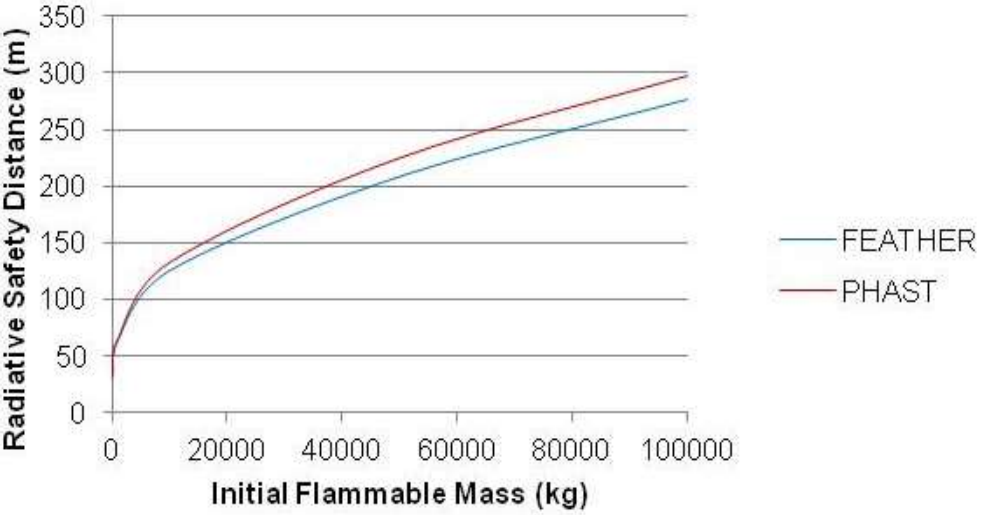

Fig. 3 – Fireball. Comparison of FEATHER vs PHAST

Distance from	Pipe rack	Assumed operating pressure bar(g)	Distance (FEATHER) (m)	Distance (Tables) (m)
To	Heat exchanger	20	90 (Jet fire) 150÷300(fireball)	10
To	Columns, Accumulators, Drums			10
To	Rundown tanks			100
To	Moderate hazard reactors			10
To	Intermediate hazard reactors			15
To	High hazard reactors			25

Table 1: Comparison of FEATHER distances (to 8 kw/m^2) with tabulated (prescriptive) distances. Jet fire and fireball.

Distance from	Intermediate hazard pumps	Assumed substance	Distance (FEATHER) (m)	Distance (Tables) (m)
To	Columns, Accumulators, Drums	Heptane	15÷35	10
To	Pipe racks			10
To	Heat exchangers			15
To	Moderate hazard reactors			10
To	Intermediate hazard reactors			10
To	High hazard reactors			10

Table 2: Comparison of FEATHER distances (to 8 kw/m^2) with tabulated (prescriptive) distances. Pool fire.

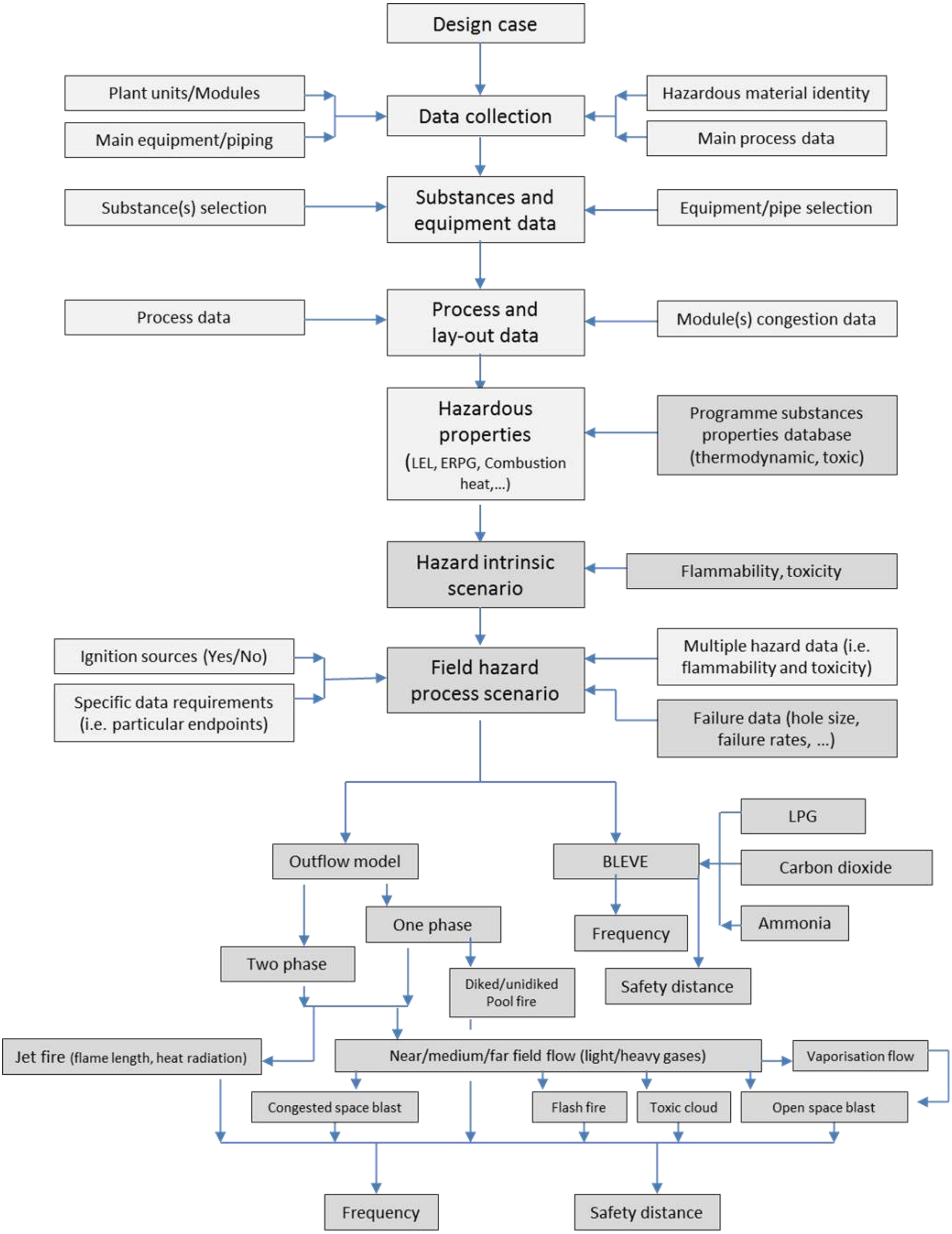

Figure 4 – Flow chart of FEATHER Software.