Fire Hazard Analysis

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CFD based Fire, Explosion and Toxicity Safety Evaluation for Nisargruna Biogas Plant

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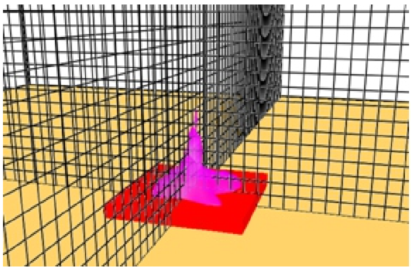

Biogas (Leak from top) volumetric concentration iso-surface between (LEL - UEL)

ABSTRACT

Fire Hazard Analysis (FHA) of a Nisargruna Biogas plant proposed to be installed at BARC hospital has been carried out to ascertain the adequacy of principles of fire safety and fire protection measures. In absence of any specific regulatory guidance on Biogas plant FHA, the generic safety objective-based FHA has been used. Defence-in-depth based dual failure philosophy has been used to evolve a suitable fire hazard methodology with objective of (i) nearly no loss of life (ii) no catastrophic effect to structure (iii) adequate fire rating (iv) no threat to public building (v) no oxygen deficiency or H_2S toxicity life loss for operator and (vi) acceptable separation distance and safety zone. A range of Design Basis Accidents (DBAs) using Computational Fluid Dynamic (CFD) analysis have been considered and these are found to have no significant life-threatening effect on the occupants in safe zone. The explosion from a hypothetical Beyond Design Basis Accident (BDBA) helps in deciding an acceptable separation distance from occupied public building and a suitable impact barrier for road or hospital canteen window.

KEYWORDS: *Nisargruna biogas plant, Fire Hazard Analysis (FHA), Computational Fluid Dynamic (CFD)*

Introduction

The Nisargruna technology has been developed at Bhabha Atomic Research Centre (BARC), Mumbai for decentralized processing of the biodegradable waste. The project has tremendous potential to support the ever-depleting energy sector by generating fuel and manure required for soil applications. The technology has evolved in last several years and about 250 such plants are operative in various parts of the country. Biogas related specific fire safety regulations are not available in prescribed codes in India [1]. Old National Building Code (NBC) permits a quantity of 2000 liters of flammable liquid but the new NBC code [2] and Atomic Energy Regulatory Board (AERB) code suggest that a large combustible material presence should be situated at outdoor or in a separate utility building [3]. The Indian Factory Act allows using unlimited quantity of oil/combustible gas for process use, subjected to certain conditions. The basis of use for such quantity is the fulfillment of mandatory nuclear safety objectives demonstrated by FHA. The AERB guideline provides the intent of the safety objectives. The number of biogas plants and accidents are growing [4-7]. Fortunately, only few of them had consequences on humans. Several reasons [8], such as leakages in storage tanks and pipes, accidental effluent discharges, sewage system overflow due to control failures or exceptional downpours, dangerous substance in the biogas raw materials, inadequate risk analysis [9], less attention to safety [10-16] and no learning from past accidents [6,7] are responsible for such accidents. In biogas plant two pertinent fire safety issues creep up. The first one is due to the methane and associated explosion. The second issue is the conventional fire and its severity due to its quantity. The FHA addresses both these issues.

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Overview of FHA Procedure

Nisargruna biogas plant is coming up in a mixed-use area near BARC Hospital, Anushaktinagar. Plant has large exits, internal free space and road which allow fast fire-fighting tender movement. The large open area and sufficiently large exit will help in easier escape for worker, natural ventilation of hot gases in event of fire and minimal chance of high temperature gas built-up and subsequent secondary fire generation. The adequate dimensions also ensure Acceptable Separation Distances (ASD) against biogas explosion. The biogas plant is proposed to be used in a low-pressure continuous utilization fashion without biogas storage and compression. The facility will have strict administrative control for the presence of human and the operation staff.

Being a first of a kind FHA, detailed study of different regulations has been done based on the following points.

(i) International consensus and Design Basis Fire Accident (DBFA) to find its impact on neighbouring structures and people.

(ii) Use of nuclear industry standard FHA approach.

(iii) Technical basis of biogas storage tank leakage.

(iv) CFD calculation of fire rating and Acceptable Separation Distances (ASD).

(v) No credit of first-hand firefighting but credit of fire tender capabilities.

(vi) CFD analysis of fire, explosion and toxicity for biogas release event.

Fig.1: Fire Hazard Analysis philosophy for Nisargruna biogas Plant.

The Fire Hazard Analysis philosophy for Nisargruna biogas plant is shown in Fig.1. The FHA is a mandatory requirement to ascertain the adequacy of principles of fire safety and fire protection measures provided in any plant for safe operational/emergency states of a plant using defense-in-depth approach [17]. In absence of quantitative regulatory procedures/guideline for ASD for biogas plant, a fire hazard analysis procedure has been developed based on (i) dual failure safety analysis and (ii) acceptable individual risk probability values.

These aspects have been used to identify the hazard sources and events (e.g. release of gas) by considering the likelihood of the events and hence, calculate the effects of fire on neighboring objects. Another objective is to determine the acceptable fire safety distance. The individual harm exposure threshold ($F_t \leq 3.5 \times 10^{-5}$ event per year) has been used for determining ASD and design fire [18,19]. However, the analysis also supports for event with lesser frequency such as gas release with storage tank breakage due to lightning on a highly conservative basis to calculate and quantify the fire risk for non-DAE public properties. Table 1 shows typical failure frequencies of biogas plant components. Category events 10^{-4} to 10^{6} adopted from AERB SG D-5 which come under the category of multiple failures and rare events are considered as DBAs [20]. The breaking of biogas boundary and subsequent release of biogas into storage building has been considered for DBA. This DBA event may lead to gas fire /explosion as per biogas triangle shown in Fig.2.

Table 1: Typical failure frequencies of biogas plant components.

Event	Probability/frequency
High pressure gas line rupture	5×10^{-4}/km-yr
Lightning strike	1×10^{-7}/yr
Severe earthquake capable of rupturing pipe work	1×10^{-6}/yr-1×10^{-7}/yr
Seal fire	Approximately 2×10^{-4}/holder-yr
Failure of a return valve on demand	3×10^{-2}/yr
Failure of an excess flow control valve on demand	1.3×10^{-2}/yr
Failure of an automatic shut off valve to close	1×10^{-2}/demand
Failure of a level sensor	50 per 10^{6} hrs
Split crown (without ignition)	Approximately 3×10^{-4}/holder-yr
Split crown explosions	3×10^{-5}/holder-yr

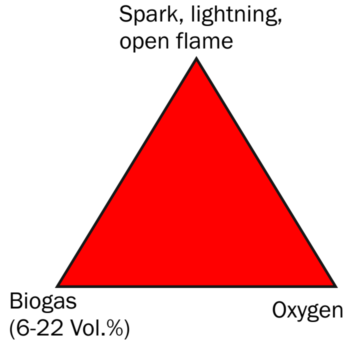

Fig.2: Biogas fire and explosion triangle.

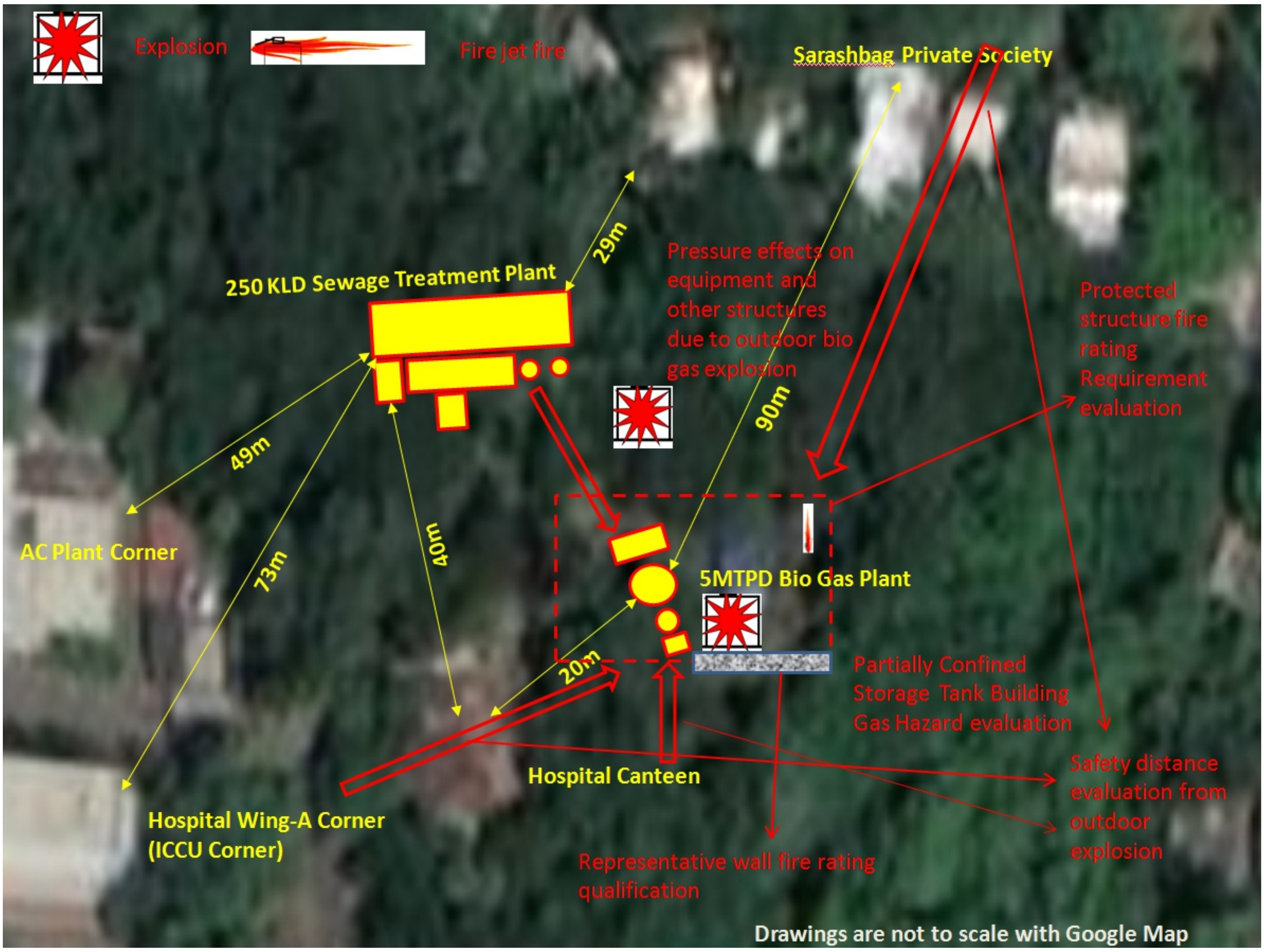

Fig.3: Schematic and fire and explosion concerns for Nisargruna biogas plant.

The Fig.3 depicts the simplified schematic and fire and explosion concern matrix (shown in sign of fire) for the present FHA. The red color star depicts the likely location of the gas explosion event. Each of the objectives i.e. external and internal gas explosion FHA, safety distance calculations and toxicity evaluations are described in the paper.

Biogas Leakage Hazard Evaluation Philosophy

The contemporary review of literature on biogas specific regulation brings some useful pointer for FHA procedure development. In Europe, safety measures against explosion risk are stipulated in Directives 99/92/EC [21]. A crucial topic as per regulations is the classification of plant areas [22]. The hazard classification in terms of various zones can be carried out based on geometrical characterization (extent and volume) of hazardous areas [23] and persistence time and cloud departure time. Hazardous Area Classification (HAC) [24] makes use of the concept of a nominal flammable gas cloud volume (V_z) in prevailing level of ventilation. HAC can be classified in various zones such as

Zone 0 – a place in which an explosive gas atmosphere is present continuously or for long periods or frequently with continuous release.

Zone 1 – a place in which an explosive atmosphere is likely to occur in normal operation occasionally with primary release.

Zone 2 – a place in which an explosive atmosphere is not likely to occur in normal operation but, if it does occur, will persist for a short time only with secondary release.

The volume, V_z, is defined as the volume within which the mean concentration of flammable gas arising from a release will be between 25 % to 50% of the Lower Explosive Limit (LEL). In the standard, the definition of the 'degree of ventilation' is applied to releases outdoors as well as indoors. Given the concept of ventilation is meaningless for outdoor releases, the gas cloud volume V_z should be seen as defining the degree of 'dilution' rather than ventilation. The standard allows the use of CFD. The value of V_z can then be used to indicate where zoning is not required through the concept of negligible extent (NE).

CFD Calculation for Design Basis Accident (DBA) Release

CFD is extensively used in process safety to calculate hazard ranges for flammable and toxic materials, heat flux in fires, explosion overpressures and toxic cloud sizes. A Large Eddy Simulation (LES) based CFD procedure (which uses Navier-Stokes equations) is used to simulate a biogas release from biogas tank which is a DBA event. A release area of 0.25 mm^2 (0.5 mm diameter) has been considered as a non-vibrating system. The details of CFD/FHA methodology are given elsewhere [25].

CFD analysis has been used to estimate the combustible/explosive cloud size. The release has been simulated in three different configurations (top, bottom and side). Bottom leak does not result in burnable cloud formation as the biogas is a buoyant gas and it will not travel in downward direction. The release from side and bottom results in the formation of burnable cloud of almost equal size. This cloud

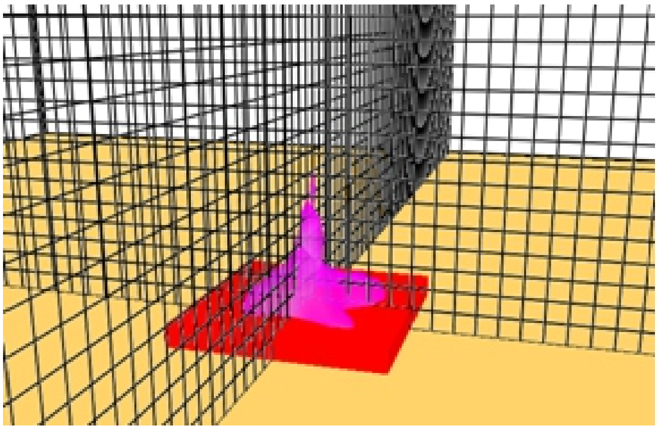

Fig.4: Biogas (Leak from top) volumetric concentration iso-surface between (LEL - UEL).

volume between Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) for top release (Fig.4) is less than 0.1 m^3 and if ignited may produce small pressure and thermal effect which is insignificant.

Design Basis Leak (DBL) of Biogas and Liquid Petroleum Gas (LPG) for Potential use in Hospital Kitchen

LES CFD analysis (using Navier-Stokes equations) of hospital kitchen has been carried out considering design basis leak of biogas and LPG [25]. Biogas being the lighter than air makes a buoyant plume and tries to move upwards and strikes with the ceiling and spreads. However, LPG being heavier than air, makes a dense gas dispersion structures and tries to make a cloud in the lower portion of the enclosure. It was found that the volumetric concentration remains less than 5% for biogas release. However, the volumetric concentration for LPG gas release is more than 15 % of lower flammability limits. Fig.5 and 6 show volumetric concentration plot at an instant of time for biogas and LPG gas respectively. Which concludes that biogas is a relatively safer option in comparison to LPG.

BDBA Biogas Release from Storage Tank

LES CFD analysis (using Navier-Stokes equations) for BDBA biogas release from storage tank has been carried out [25] the building consisting biogas storage tank is the biggest safety concern area. In most of the DBA accident the biogas cloud size is insignificant. But in BDBA situations where a much higher quantity is coming out in atmosphere has to be analysed using CFD methodology for various possible leak sizes from the storage building. The green color obstacle is added to represent the storage building wall (in order to capture the realistic mixing around the source) in all large release area situation and in small area releases it is assumed at the domain only. The conservative quantity of combustible /explosive cloud was estimated with the help of clouds size (Fig.7) then, explosion/blast wave estimation were carried out using the experimental data from the literature as shown in Fig.8 [26].

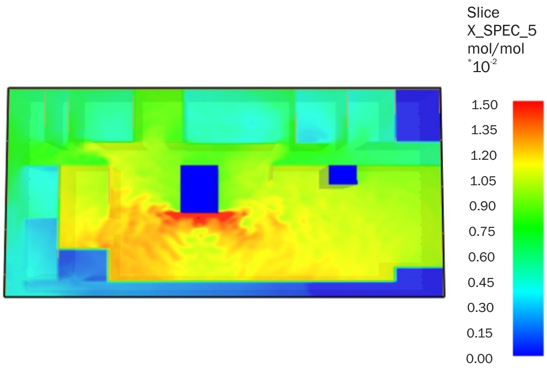

Fig.5: Biogas release volumetric concentration.

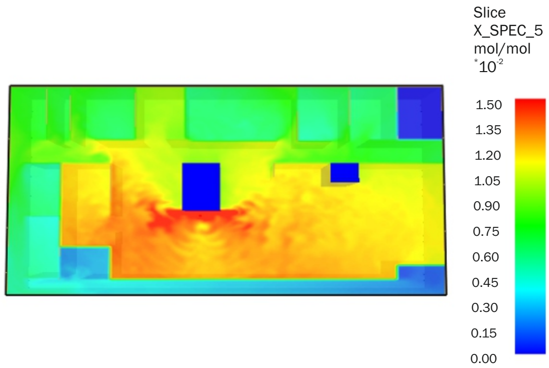

Fig.6: LPG release volumetric concentration.

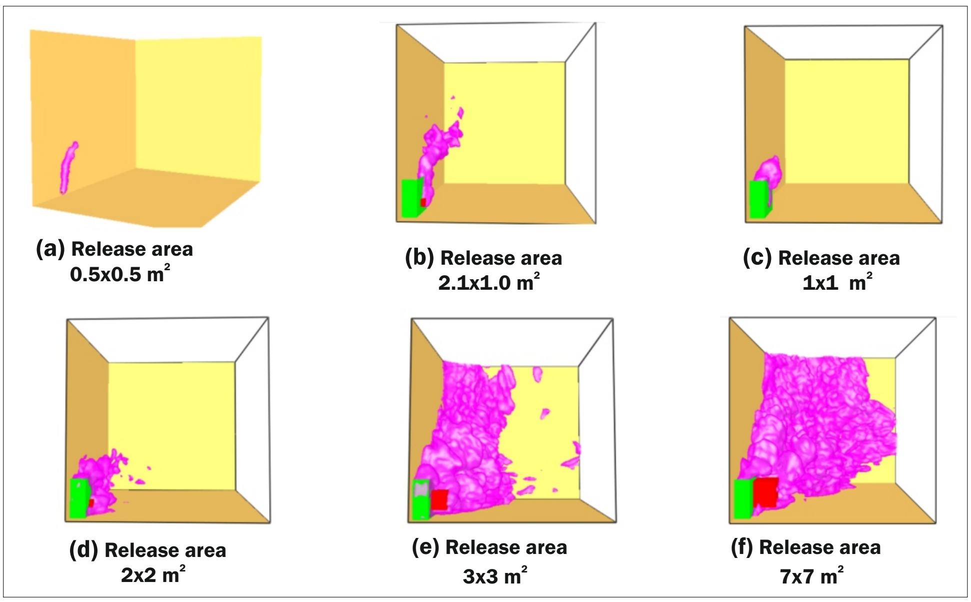

Fig.7: Biogas volumetric concentration cloud between 5% - 15%.

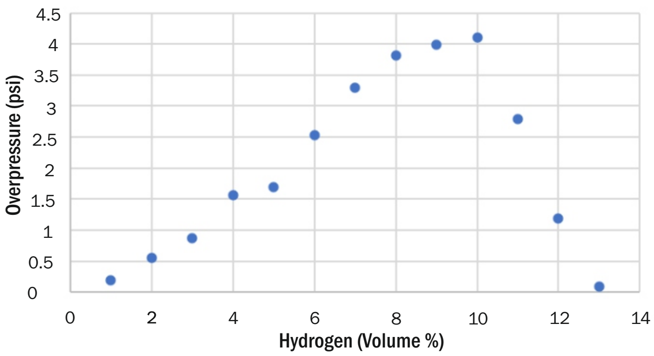

Fig.8: Average overpressure vs. concentration for small volumes of hydrogen.

Fig.8 shows overpressure for different hydrogen concentration cloud size which is generated nearly based on 200 experimental tests performed for volumes ranging from 340 litres to ~1850 litres utilizing spark igniters [26]. The data from the Fig.8 has been used in the present biogas fire hazard analysis with suitable energy severity corrections (biogas equivalent hydrogen).

In present situation, a biogas equivalent hydrogen quantity of about 123 liters is estimated from CFD which reside in biogas explosive cloud. Pressure rise calculation with a linear risk extension approach is as follows.

Pressure rise in biogas accident = biogas equivalent hydrogen quantity x pressure rise in reference case/ hydrogen quantity in reference case

123 x 4.25/340 =1.5375 psi or 0.106 bar

The pressure rise is found to be only 0.106 bar and will not pose any threat to building structure near (at least 11 ft away) to the facility. For a moderate damage to happen the overpressure should be more than 2.0 psi. But this kind of pressure rise requires demonstration of the risk in terms of death and ear injury by a Probit (probability + unit) regression analysis. It was established that the probability of death is negligible but ear damage probability is almost 10% and use of ear plug is advised at certain zone for longer stay. The biogas equivalent hydrogen combustion values shown above were used to find out the minimum separation distance in terms of Trinitrotoluene (TNT) equivalent [27]. So, for about 19.22 lb of TNT equivalent the minimum distance for failure of a concrete column is of the order of 11 feet and about 50 ft for glass breakage calculated from the Fig.9. Fig.9 shows safe distance against the explosive yield in TNT for different material of concern. Alternatively, suitable metal plates can also be placed to reduce safe distance for permissible limit against vulnerable location.

Biogas Toxicity Simulations

The concern was addressed for biogas toxicity (almost nonexistent as per designers) by taking a conservative H_2S fraction in biogas. The LES CFD (using Navier-Stokes equations) based H_2S dispersion study was carried out [25]. The biogas toxicity cloud due to H_2S is calculated for a range of DBA and BDBA scenarios by varying the size of break in storage building. The most likely conservative DBA case would be the door with a 2x2 m of size (shown in red color) (Fig.10-a). The iso surface reveal that the toxicity cloud exists only near to the release location except for a larger BDBA scenario (Fig.10-b). It is suggested to create a safety zoning and administrative access control neat the biogas storage area.

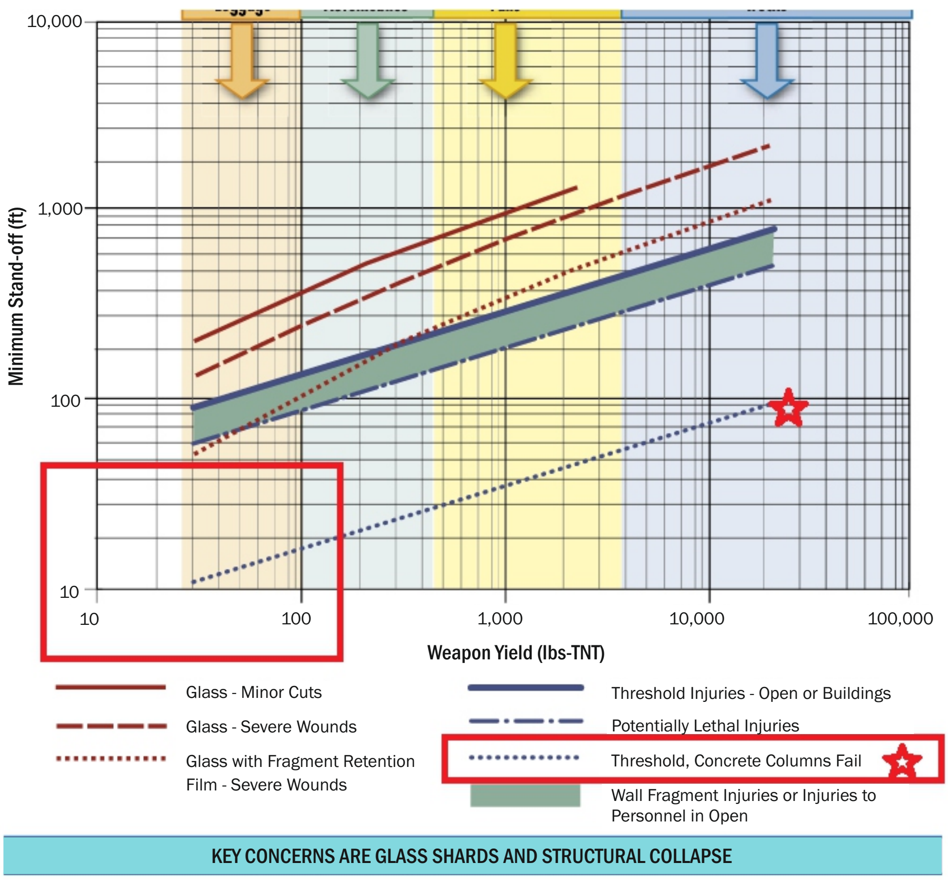

Fig.9: Safe distance against the explosive yield in TNT.

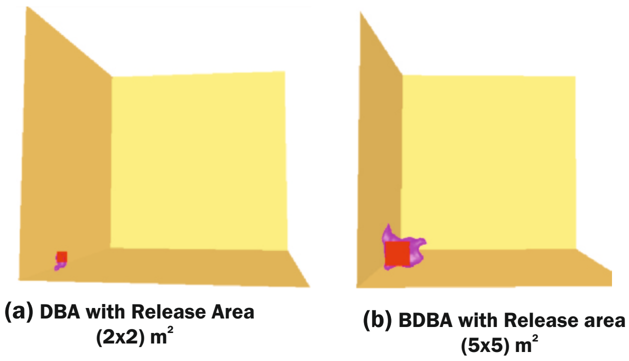

Fig.10: Biogas volumetric concentration cloud between 5% - 15%.

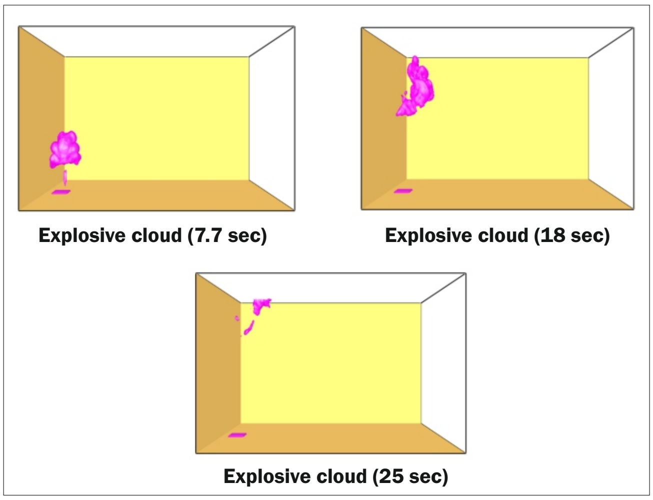

Fig.11: Biogas volumetric concentration cloud between 5% - 15%.

Cloud safe departure time calculation for Nisargruna plant for BDBA

The LES CFD simulation (using Navier-Stokes equations) have been carried out for complete biogas release (Storage tank area) instantaneously and safe departure time is calculated for safe movement of cloud upward [25]. The departure time depends upon the size and quantity of biogas plant. The cloud safe departure time calculation for Nisargruna plant at different instant of time is depicted in Fig.11 (the bottom face square is the injection and top moving iso-surface is the combustible cloud). The cloud covers a safety distance of about 150 m in about 30 second. The cloud moves away from the ground building and will keep on diluting. These purely hypothetical (unlikely) situation simulation results stress upon the need to strict ignition and fire sources control by a strong safety culture which will result in safe departure phenomenon along with passive dilution within a minute to keep the structure around the plant and worker safe. For this cloud size an ASD of 75 m was found to be adequate.

Conclusions

A CFD based first-of-its-kind fire hazard analysis approach of biogas plants against fire, explosion and toxicity related regulatory concerns has been developed. The developed methodology was used to qualify the Nisargruna facility at BARC hospital. The regulatory requirement in terms of explosive cloud size, toxic cloud size, explosion over pressure, acceptable separation distances, safe departure time and safety zoning was established. FHA for a range of DBA and BDBA events concluded no significant life-threatening effect on the occupants in safe zone, public building and hospital kitchen. The CFD analysis has also depicted the relative safe nature of biogas over LPG. The biogas safety aspects (fire, explosion & toxicity) found to be safe during its utilization in hospital kitchen.

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