# CHAPTER 6
# INCIDENT MODELLING

## 6.1 INTRODUCTION

6.1.1 In an analysis of this nature, the failure scenario is examined in detail All possible outcomes of every failure identified are assessed, taking into account the size and nature of the failure, the process parameters prevalent at the point of the release and the weather conditions.

6.1.2 Normally, the factors analysed are dispersion distances (Lower Flammability Limit or ***LFL***) of the substance released, the probable radiation from any fire that results, and the possible shock wave and domino effect upon equipments and structures that could arise from an explosion, should one occur.

6.1.3 A very important factor to be borne in mind is that volatile petroleum products such as MS will form substantial amount of vapour if it is allowed to leak for considerable amount of time, and the flammable material will spread further if the leak is allowed to spread beyond dyke to a larger area. The vaporisation in the present case was higher as the MS pool resulting from loss of containment was not confined to the dyke but spread over a much larger area of the Terminal Plot through storm water drains. Further, high velocity vertical jet of MS emanating from Hammer Blind could lead to enhanced MS carry over into rhe vapourized mass through wind losses through entrainment.

6.1.4 Explosion mechanism of inflammable vapours envisages the formation of an “Explosive Mass” which is the quantity of vapour formed within “Lower Flammability Limit” (LFL) and “Upper Flammability Limit” (UFL). The quantity of explosives mass determines the effect of the explosion blast. The time required for forming the explosives mass will be dependent on rate of vaporisation which, in turn will depend on “vapour Pressure of the liquid which “vaporises” and the “liquid pool area” resulting from “loss of containment” and also to an extent on “ nature of loss of containment

(rate/velocity of release, direction i.e. horizontal/vertical). Based upon these calculations, effect zones for each of the outcomes are determined, to reveal what facilities or installations were likely to have been affected by the scenarios investigated.

## 6.2 SCENARIOS INVESTIGATED IN THE ANALYSIS

6.2.1 In a consequence assessment dealing with refinery process and storage facilities, which primarily handle hydrocarbons, the possible scenarios that merit investigation are:

1. Fires
    a. Flash Fires
    b. Pool Fires
    c. Jet Fires
2. Explosions
    a. Unconfined Vapour Cloud Explosions (UVCE)
    b. Boiling Liquid Expanding Vapour Explosions (BLEVE)

6.2.2 Flash Fire – A Flash Fire, in effect, is a sheet of flame that moves through a cloud of gaseous or vaporised hydrocarbons, without any accompanying shock-wave. It rarely lasts for more than a few seconds, and causes little damage to equipment and installations, but is fatal to individuals in its path.

6.2.3 Pool Fire – A Pool Fire is a fire on a stationary liquid surface, such as that of a pool of liquid hydrocarbon. The nature of the flame depends upon the fuel burning, with more smoke being generated by heavier hydrocarbons on fire. Its thermal radiation can affect all individuals and facilities in its vicinity, but its intensity depends upon the volume available, and the duration of the fire.

6.2.4 Jet Fire – A Jet Fire occurs when a hydrocarbon release from a pressurised source is ignited close to the source of the release. It is, for all practical purposes, a jet of flame that will last as long as the supply of fuel lasts under pressure and whose radiation and effect zone, depend as much upon the fuel as on the pressure at which it is released. In addition to damage inflicted by thermal radiation, the flame can also cut through metal, if it were to impinge upon the metallic surface, setting off a domino effect.

6.2.5 Unconfined Vapour Cloud Explosion – A UVCE is similar to a flash fire, except that in addition to the flame front, a pressure front, generated by the fire, moves through the cloud, at speeds of 100 $^{m}/_{s}$ or greater.

6.2.6 Boiling Liquid Expanding Vapour Explosion **–** A BLEVE occurs when a liquefied, or occasionally a liquid, hydrocarbon is contained in a vessel exposed to an external fire. The fire weakens the shell of the vessel, while also causing the hydrocarbon to boil, thereby pressurising the vessel. Once the vessel's pressure exceeds the threshold limit of the metal, the shell would fail spilling out the rest of the hydrocarbon, which would then undergo an explosion or a fireball.

## 6.3 SCENARIOS APPLICABLE TO THE INCIDENT AT THE SANGANER MARKETING TERMINAL, JAIPUR

6.3.1 Flash Fire: When the cloud came in contact with a source of ignition, it would have undergone a flash fire, which flashed back to the source of the leak in the MS Tank outlet manifold, igniting the fuel spilt. This would have been fatal to all individuals in the area but would not have damaged any structures or equipment.

6.3.2 UVCE***:*** Considering that the leak and subsequent dispersion occurred for well over one hour and a quarter, sufficient mass is likely to have accumulated in the cloud, for the flash fire to accelerate into a UVCE. The overpressure from such a UVCE would have extensively damaged the

Administrative Building, Control Room and other buildings, as well as the tanks, besides igniting the fuel accumulated in the tank bund.

6.3.3 Pool Fire: With the flame-front of the UVCE acting as a source of ignition, the fuel in the bund would have been ignited. Since fuel from the spill had been accumulating for more than an hour, the radiation from the Pool Fire would have caused some amount of damage to the tanks in the vicinity.

## 6.4 MODELING AND ANALYSIS

6.4.1 The distance covered by the vapour cloud arising out of huge loss of containment of MS in Jaipur and the damage contour in the vapour cloud explosion was determined using the well known software “PHAST 6.53” (a software developed by DNV). However, this software considers/restricts calculations for one hour leak. This itself shows that the scenario as it happened in Jaipur i.e. loss of containment beyond one hour, was never considered a credible accident scenario even by globally established expert safety consulting firms such as DNV. However, in the absence of any better software, the Investigation team was constrained to model the consequent scenario using PHAST 6.53. The loss of containment was considered to happen in 1.5 D weather conditions, i.e. with a wind velocity of 1.5 m per second and absolutely normal weather conditions. There was approx., 75 minutes interval between the perceived start of the leak and the explosion. Though the model here considered one hour leak duration, it must be observed that the additional vaporisation that would have occurred over the extra 15 minutes further add to the hazard, due to increased vaporisation of MS.

6.4.2 MS considered in this model is composed of 36.5 mole % Pentane and 63.5 mole % of Hexane, in the liquid state at 35o C at atmospheric pressure being released from a hydrostatic head of 12 m as reported in the incident, without overflowing for the tank in question (401-A).

## MS PHYSICAL PROPERTIES

| Test | Method | Specification | |
|---|---|---|---|
| Grade | | MS 91 | MS 95 |
| Density @ 15oC, kg/m3 | P : 16 | 720-775 | 720-775 |
| Colour, Visual | | Orange | Red |
| Copper Strip Corrosion (3 hrs. @ 50oC) | P : 15 | Class 1 | Class 1 |
| Existent gum (gm/m3) | P : 29 | Max. 40 | Max. 40 |
| Lead Content (as Pb), gm/litre | IP 352 | Max. 0.005 | Max. 0.005 |
| Research Octane Number (RON) | P : 27 | Min. 91 | Min. 95 |
| Motor Octane Number (MON) | P : 26 | Min. 81 | Min. 85 |
| Reid Vapour Pressure @ 38oC, kPa(4) | P : 39 | Max. 60 | Max. 60 |
| Distillation | P : 18 | | |
| Recovery upto 70oC, %v | | 10-45 | 10-45 |
| Recovery upto 100oC, %v | | 40-70 | 40-70 |
| Recovery upto 150oC, %v | | Min. 75 | Min. 75 |
| FBP, oC | | Max. 210 | Max. 210 |
| Residue, %v | | Max. 2.0 | Max. 2.0 |
| Benzene content, %v | ASTM D3606 | Max. 1 | Max. 1 |
| Total Sulphur, %wt. | ASTM D2622/ D5453 | Max. 0.015 | Max. 0.015 |
| Vapour Lock Index (VLI): a) Summer (5) | | 750 | 750 |
| b) Other months (Winter) | | 950 | 950 |
| Oxidation Stability, minutes | P:28 | Min. 360 | Min. 360 |

| | | | |
|---|---|---|---|
| Olefin content, %v | ASTM D1319 | Max. 21 | Max. 18 |
| Aromatics content, %v | ASTM D1319 | Max. 42 | Max. 42 |
| Oxygen content, %wt. | ISO 1601 | Max. 2.7 | Max. 2.7 |
| Oxygenates content, %v | ASTM D4815 | | |
| a) Methanol | | Nil | Nil |
| b) Ethanol | | Max. 5 | Max. 5 |
| c) Iso-propyl alcohol | | Max. 10 | Max. 10 |
| d) Iso-butyl alcohol | | Max. 10 | Max. 10 |
| e) Tertiary-butyl alcohol | | Max. 7 | Max. 7 |
| f) Ethers containing 5 or more carbon atoms per molecule | | Max. 15 | Max. 15 |
| g) Other oxygenates | | Max. 8 | Max. 8 |
| Engine intake system cleanliness (7) | As per IS 2796 | Report – MFA used | Report – MFA used |
| Water Tolerance of gasoline alcohol blends, temperature for phase separation, oC, | | | |
| a) Summer | | Max. 10 | Max. 10 |
| b) Winter (6) | | Max. 0 | Max. 0 |

6.4.3 The loss of containment scenario that has been assessed is as follows:

- A vertical release with an aperture of a diameter equivalent to 12” x6” size as in actual case it was a vertical case.
- A full – bore rupture of the 10” outlet line of the tank, since the cross section of this pipeline is smaller than the failure aperture of the hammer blind valve, and would act as a limiting factor.

6.4.4 The formation and spread of the vapour cloud has been examined for the following cases:

- Wind direction from MS tank farm towards TLF (north to south) at 23o east of north.
- Wind direction from 23o west of north.

6.4.5 These two scenarios have been considered to account for the plant personnel observations that:

- The wind from the MS tank to TLF area
- And the wind north easterly direction

6.4.6 The extent of the vapour cloud has been plotted in Figures 4 a, b and 5 a, b. It is repeated that vapour cloud had covered a major area of the facility and the stimulated impact of the subsequent fire and explosion (s) is indicative of the damage that was observed at site. The vapour cloud plots have been further supplemented with plots of vapour dispersion from the drainage system at two locations namely, tank dyke and ETP. These essentially indicate that the vapour clouds formed by a major leak at the hammer blind valve of 401-A got supplemented by a number of other clouds that had formed along with the drainage system around the tank farm.

**6.5.** As an alternative scenario, it was considered that the outlet line of the tank had given away in a full bore rupture, and that MS released would form a liquid pool in the dyke area, before vaporising during the time that lapsed between the start of the release and its ignition.

Case 1 Line rupture

Weather condition 1.5 D

After one hour

Mass released = 790,096 Kg

Mass vaporised = 67,753 Kg

Vaporisation rate = 18.54 kg/s

LFL distance = 200 m

Refer figure 4.a

**6.6. Case 2 : Vertical release**

6.6.1 Since a jet fuel was observed at the start of the incident, the release was modeled so that the substance would spout out as a jet, and land 6.10 m away, before forming a pool that would vaporise during the time that elapsed between start of the release and the ignition.

Weather condition 1.5 D

Angles of release 10º & 20º

After an hour:

Mass released = 600,000 Kg

Mass vaporised= 33,000 Kg

Vaporisation rate= 8...50 kg/s

LFL distance= 325 m

Refer Figures 5 a,b

6.6.2 It is evident from the plots that depending on the wind direction, specific areas of the plant can come within the parameter of the cloud. However, going by the most prevalent wind direction, as well as the wind directions that was supposedly prevailing at the time of the incident, the major facilities would have come inside the area were concentration of MS vapours was within inflammable limits. The presence of vapours along the storm water drains would add to a bigger consequence.

## 6.7 IGNITION

6.7.1 When the concentration of liquid hydro carbons (HC) as MS in the HC-air mixture falls within the inflammable limit between (1.2% and 7.2% of MS vapours), a fire will occur immediately in presence of an ignition source which can be a spark or an open flame. Source of ignition may be:

- Auto ignition. However in the present case it is ruled out as the product was stored well below auto ignition temperature.
- Electrical apparatus covering machines and fittings in which conductors are used and of which they are a part, namely, electric switches, push buttons, socket plugs, circuit breakers, instruments, motors and so on, these may act as a source of ignition by electrical Arcs and sparks raising the surface temperature of the apparatus above auto ignition temperature. Such possibility cannot be rejected outright as there were a number of buildings with electrical fittings, more specifically, the BCC building and control room had PCs and associated wiring and electrical fittings on the top floor. The location where PCs were housed showed signs of fire damage and one of the scenarios examined while plotting the contours of the blast considered this location as a possible location of ignition source.
- Static electricity. This was not considered as the factors leading to static electricity generation did not apply.
- Lightning. This also does not apply. In this case as weather conditions were good.
- Non-electrical ignition sources include IC engines, Pyrophoric iron, frictional impact/falling of iron tools etc. Out of these, first cause has been examined as it was found efforts were made to start a jeep in pipeline division gate. A case has also been examined for a motor cycle in a road behind a SKO tank 402-B. Although the possibility of its engine being on appears remote as the motor cycle stand is out and hence presumably stopped by the rider, whose body was later found on the same road behind tank 402-C. However, the possibility of the rider trying to restart the motor cycle cannot be ruled out and hence this case too was examined.

6.7.2 Going by the consequences observed, the more serious of which were restricted to the facility, although explosion damages occurred outside as well, the source of ignition was certainly within or close by the facility. In this regard there could also be a possibility that cloud is ignited by kitchen fire in a building immediately east of the facility.

6.7.3 Ignition occurred within 75 to 90 minutes after the leak began. Therefore, the source of ignition was available only 75 to 90 minutes after the leak. Accordingly ignition could not have been by any pre-existing source inside the tank terminal.

6.7.4 This leads to the possibility of ignition source as either on electrical spark from a running engine or a spark vehicle/motor bike through the flammable range of the cloud.

6.7.5 There were no tankers in the TLF shed at the time of ignition. Other points which refute the possibility of ignition source at TLF is the shock-wave pattern, since all light masts in the administrative building have been bent towards south east rather than away from it, as may be expected if the explosion originated through ignition source at TLF shed.

6.7.6 As per security personnel statement a mist of MS vapour had formed in the area prohibiting vehicular movement from the gate towards the facilities located inside. . Thus the possibility of extra ordinary vehicle movement from the main gate towards the tank farm as an ignition source is precluded. However personnel in the pipeline division, who, too would have to travel along the roads to tank farm through approach the main gate, would have to start their vehicles (a jeep and a motorbike). There are possibilities of spark from either of these vehicles. Coming to the possibility of electrical sparking, most sparking occurs when the

equipment is started or shut down. From all information available, none pointed towards any attempt by any personnel in the facility to start or shut down any electrical equipment around the time vapour cloud ignited. Though there are provisions for auto start of the emergency back up generators both for SAP server as well as pipeline division, these could not have been started as neither any grid failure was reported nor had the state electricity board switched off the supply before the blast.

6.7.7 Therefore, only possible source of ignition which were likely are follows:

1. Motor bike engine of one of the pipeline division officer - However, in this case the stand of the motor bike was in out position which indicated the motor bike was parked on the northern side of the SKO tank and the body of the rider was found some distance away. In all likelihood the motor bike engine stalled due to lack of enough air in the air-fuel mixture and the rider after parking the vehicle ran towards a safe area. The motor bike rider who eventually died in the blast was the morning shift officer of the pipeline division who stayed back in the pipeline division even after his duty hours were over (2.00 p.m.). One intriguing fact which could not be explained to the satisfaction of the investigating team is why the morning time shift officer stayed back long hours after his duty hours were over.
2. The pipeline division jeep driver in all likelihood repeatedly tried to start the jeep which failed to start again because of insufficient air-fuel mixture. If the vehicle would not have started, no sparking is possible (diesel engine). Even if the vehicle would have started, being fitted with a spark arrester of standard design, no spark at exhaust pipe is feasible. However, if the vehicle starts and the spark arrester is defective or not there, the chance of which is remote, a spark generation may be possible.
3. As mentioned in the foregoing,the upper floor of the BCC building, where the computers were located, shows distinct signs of fire damage. Some of the structures and trees also appear to be bent towards the MS tanks,

indicating a possible source of ignition in the BCC/DG building area and causing the subsequent blast(s) If the source of ignition was within the BCC building, the initial extent of the blast would be quite limited as the quantity of Hydrocarbon vapour present inside would be quite low depending on the air change rate followed.However , once the blast occurred, it would expose the fire to the vapour cloud that was present outside and create a flash back to the MS tank as well as the subsequent explosion(s)that occurred.The fact that witnesses at the site mentioned seing a streak of light followed by a major cloud of smoke rising into the sky,seems to corroborate this hypothesis.

**6.8** The nature of explosion damage strongly points to the ignition source being in pipeline division area or in the location around the BCC/DG buildings The exact location and the reason of its initiation could, however not be established so far.

1. Depending on the location of the ignition source, the key facilities/buildings are subjected to overpressures that are high enough to cause significant damage.
2. The extent of the damage on account of fire and resulting explosion has been accentuated by the spreading of hydrocarbon liquids into the storm water network, which encircles all the facilities/buildings.
3. The uncontrolled leak over a period exceeding one hour led to the release of almost 700-800 tons of motor spirit (in actual case, quantities would be higher as PHAST model considered only 60 minutes leak) and resulted in unprecedented damage. It may have been possible to limit the damage to the tank farms had all the leak been contained within the tank dyke and the fire water system been operative.

4. As can be seen from the various plots, certain combinations of wind direction and ignition source can cause a fire and explosion resulting in the extensive damage that occurred.

**6.9** The cloud attained a maximum LFL distance of 323 metres about 7min 45 seconds after the start of the release. Since this is no different from the LFL distance 1hr 15 min after the leak started ,i.e. when the explosion actually occurred ,the damage resulting from a flash fire would have been similar in both cases, but the damage on account of an explosion would have been much lower.

| S.No. | Time of explosion(s) | Mass involved (Kg) | Overpressure distances (m) | | |
|---|---|---|---|---|---|
| | | | 5 psi | 3 psi | 2 psi |
| 1 | 467.2 | 4,416.7 | 99.15 | 135.33 | 174.93 |
| 2 | 4500 | 39,808 | 451.82 | 499.92 | 552.56 |

As will be seen from the results, the distance attained by shock waves from an early explosion would be much lower than that attained by the shock waves of a later explosion, on account of the very great difference in mass involved. Had an explosion occurred early on, facilities more than 200 m away from the point of ignition would have emerged unscathed from the incident.

**6.10** On the other hand, were a flash fire to occur instead of an explosion, most equipment have been damaged, since a fire is an instantaneous phenomenon, causing the same damage in the area of its spread irrespective of mass involved or time elapsed. Once the flash fire had consumed the vapours generated from the released substance, the conflagration would have been sustained by the material split from the

tank, and contained within the dyke. Thus, a localized pool fire would have ensued.

**6.11** The simulations were repeated using alternative methods and the results generally corroborated the findings of the incident modeling. These are briefly discussed in the following paragraphs.

### 6.12 Vaporisation from Liquid Pool

From Page 3.38, Yellow Book (3rd edition, 1997), mass transfer coefficient is given by

$$k_m = 0.004786\,(u_w)^{0.78}\,(2\,r)^{-0.11}\,(Sc)^{-0.67}$$

where, $k_m$ is mass transfer coefficient (m/s), $u_w$ is wind speed (m/s), r is the pool radius (m) and Sc is Schmidt number.

Assuming $u_w$ = 3 m/s and Sc = 0.8 (a typical value for hydrocarbons),

$$k_m = 0.013\,(2\,r)^{-0.11}$$

Further assuming motor spirit to be equivalent to n-hexane, vapour pressure at 25 ºC is 151 mm Hg. This gives concentration of hexane in air at saturation to be 0.7 kg/m$^3$.

Then, evaporation rate q (in kg/h per m$^2$) is given by

$$q = k_m \, C = 32.76 \, (2 \, r)^{-0.11}$$

Substituting various values of r, we get:

| R | q (kg/h per $m^2$) |
|---|---|
| 50 m | 19.74 |
| 100 m | 18.3 |
| 200 m | 16.95 |

Take a value of 18 kg/h per $m^2$.

Assuming an outflow rate of 1000 tones per hour and allowing 10% evaporation during initial rain-out, the pool area at steady state is (900 x 1000) / 18 = 50,000 m2.

**This gives a pool diameter of 252 m.**

Tank 401A Leakage Rate calculation:

Tank Dia = 24M, Vol/M Ht. = 0.7854*24*24 = 452.4 M3

Vel. = √2 gh = 4.429*√h

MS Sp.grv = 0.7

1) Assume tank dia = 24 M, initial height of liquid = 11 m, liquid height after time t = 7 M. This gives a total volume outflow = 1809.6M3 or 1809.6KL.

2) At 250 mm dia outflow pipe, assuming full-bore flow, leakage area = 0.049 m2.

3) Assume an average liquid head of 9.5 m in the tank during the above leakage period and also a discharge coefficient of 0.61. This gives a volumetric outflow rate of 0.40 M3/Sec, or 1440 M3/Hr. ie 1440KL/Hr, **Release rate = 1000T/Hr**

4) Therefore, time required for 1809.6 KL to flow out = 1809.6/1440 = 1.25 h = 1 h 15 min

**5) Total mass outflow during this period is 1809.6* 0.7=1266 MT**

## 6.13 VCE Blast Pressure Calculation:

Calculation of flammable mass for continuous emission from an area source would be very involved. Inaccuracy are involved due to many assumptions which may be debatable .

Therefore, for an order of magnitude estimate, one can use an approximate empirical correlation due to J. G. Marshall, quoted in Lees (page 15/290). Assuming motor spirit to be equivalent to hexane, flammable conc. limits to be 1.2% and 7.4% by volume, and heat of combustion to be 45000 kJ/kg, stable category F for weather, 3 m/s wind speed and 1000 te/h emission rate, flammable mass in the cloud has been estimated to be 8.8 te.

**For the above flammable mass, and assuming TNT model, severity of damage has been estimated to be as follows:**

- At 200 m radius, estimated overpressure is 9.4 kPa (Not habitable without major repair work. Roofs fail partially and 25% of all walls fail with serious damage to remaining carrying elements. Damages to window frames and doors).
- At 400 m radius, estimated overpressure is 3 kPa ((Habitable after relatively easy repairs. Minor sturctural damage).
- At 750 m radius, estimated overpressure is 1.1 kPa (Damage to roofs, ceilings, minor crack formation in plastering, more than 1% damage to glass panels).

## 6.14 CONCLUSIONS

The modeling of the leak and generation of explosion contours was based on the evidence gathered during the site visits and interactions with various personnel and agencies. It was carried out with the objective of ascertaining whether the circumstances leading to the loss of containment and the subsequent explosion and fire would have caused the devastation that occurred. The steps involved in this exercise were as follows:

- Modeling of the leak to confirm the observation of eye witnesses regarding the fountain like emission of MS from the Hammer Blind opening at the outlet of tank 401-A.

- Modeling of vapour cloud formation and the extent of its dispersion to verify that vapours had spread all over the plant and that it was impossible to approach the tank valve manifold.

- Modeling of the explosion contours to verify the extent of damage that had occurred.

The modeling of the leak as depicted in figures 12 (a) and (b) indicates that the MS would have spilled out as a jet at high velocity and reached a height of about 10 meters before spilling back on the ground about 10 meters away. This continued for almost 75 minutes resulting in the accumulation of a huge quantity of MS in and around the tank dyke.

The dispersion of MS vapours from the leak led to the formation of a vapour cloud extending to a distance of almost 335 meters. Except for the area immediately adjacent to the leak source, the concentration of MS in the cloud ranged between 1.2% and 7.8% i.e. the lower and upper flammability limits of MS. This implies that the facilities covered by the vapour cloud would be vulnerable in the event of a fire. These include the non plant buildings, TLF facilities, fire water system, portions of the pipeline terminal etc.

The vapour generated during this period was about 40 tons and posed a great hazard even in the absence of fire, as prolonged exposure to MS could have consequences ranging from giddiness and drunkenness to paralysis and even death. This would explain the conditions of M/s. RN Meena and AK Gupta when they were seen by Mr. Chambal Singh. It also explains the inability of the plant/security personnel to approach the source of leak especially without any PPE like self contained breathing apparatus, safety glasses etc.

The modeling of vapour dispersion corroborates the observations of plant personnel that MS vapours had spread over large areas of the facility.

The evidence/observations as elaborated subsequently in Chapter 7, point to the following possible locations which could have provided the ignition source:

- BCC buildings, where definite indications of fire damage are visible.

- Pipeline terminal, where hot metallic surface(s) could have present in the pump (diesel driven) of pump house.

This is based on the nature of damage that has been observed and eye witness accounts of a streak of light (flame) followed by a huge explosion and secondary explosions.

In the event that prevalent weather conditions and the turbulrnce of a cloud permit sufficient sufficient mixing with air, an Unconfined Vapour Cloud Explosion ( UCVE) can occur when the cloud encounters a source of ignition. The flame front moves through the cloud fast enough to compress the surrounding air into a shock wave and facilities within the overpressure distances of the blast will be damaged. The table below indicates the effects of different levels of overpressure:

| Blast Overpressure ( psi) | Damage level |
|---|---|
| 5.0 | Major structural damage; fatal to people indoors |
| 3.0 | Oil Storage tank failure |
| 2.5 | Ear drum rupture |
| 2.0 | Repairable damage: light structures collapse |
| 1.0 | Window Panes shatter: light injuries |

From the overpressure contours that have been generated, the following scenarios are plausible:

- A fire/blast could have occurred in the BCC building with a shock wave of 5 psi extending to about 77 meters (Fig.10). The damage to the walls, windows etc., would have exposed the fire to the MS vapour cloud,

leading to a delayed UCVE with a consequential dyke fire and tank roof failure, on account of pressurization of the tank by the dyke fire ( Fig 3). The radiation on account of the tank fire was enough to cause a roof damage in the adjoining tanks through pressurization (Fig.6).

- Ignition from the pipeline terminal side would have created a blast with explosion contours as depicted in Fig 5. This would damage the MS followed by similar consequences as above.

The modeling corroborates the observation at site and an inference that could be drawn from this is that such eventualities should form part of a quantitative risk analysis for approval/clearance for similar facilities are granted.

The cases examined and the accompanying plots/graphics are annexed to this chapter.

***Figures 1a & 1b***

The figures depict the dispersion of motor spirit vapours, spilt by the full-bore rupture of a 10” line, under 1.5D weather conditions, with the wind from 20° East and West of North, in Figures a and b respectively. The distances from the source of the release are:

UFL Distance (green) = 81 m

LFL Distance (blue) = 216 m

***Figures 2a and 2b***

The figures depict the dispersion of motor spirit vapours, spilt by a 12”x6” hammer blind assembly failure, under 1.5D weather conditions, with the wind from 20° East and West of North, in Figures a and b respectively. The distances from the source of the release are:

UFL Distance (green) = 45 m

LFL Distance (blue) = 337 m

***Figure 3***

The figure depicts the delayed explosion of motor spirit vapours, released over 1 hour by a hammer blind assembly failure, under 1.5D weather conditions, with the wind from 20° East of North and the DG Set acting as the source of ignition. The distances from the epicentre of the explosion are:

5 psi (blue) = 254 m
3 psi (yellow) = 346 m
2 psi (green) = 448 m
1 psi (red) = 710 m

***Figure 4***

The figure depicts an explosion that could arise if the motor spirit vapours were to disperse to the north of the MS Tank Farm, and be ignited by a motorcycle there. The distances from the epicentre of the explosion are:

5 psi (blue) = 254 m
3 psi (yellow) = 346 m
2 psi (green) = 448 m
1 psi (red) = 710 m

***Figure 5***

The figure depicts an explosion that could arise if the motor spirit vapours were to disperse to the east of the MS Tank Farm, and be ignited by the Pipelines Jeep there. The distances from the epicentre of the explosion are:

5 psi (blue) = 254 m
3 psi (yellow) = 346 m
2 psi (green) = 448 m
1 psi (red) = 710 m

***Figure 6***

The figure depicts a pool fire of motor spirit spilt in the dyke from a hammer blind assembly failure, under 1.5D weather conditions. The diagram helps infer the radiation from the fire that would be necessary to account for a roof failure such as that considered for Figure 9. The distances from the centre of the fire are:

8 $kW/m^2$ (green) = 42 m

4 $kW/m^2$ (blue) = 69 m

***Figures 7a & 7b***

The figures depict the dispersion of motor spirit vapours, evaporated from the MS Tank Farm Storm Water Drain, under 1.5D weather conditions, with the wind from 20° East and West of North, in Figures a and b respectively. For the purpose of calculations, the storm water network was divided into discrete lengths, each of which could act as an independent source. The MS Storm Water Drain was considered to be 130 m long, 1 foot wide and 1.5 feet deep, with MS to half its depth. The distances from the point of the release are:

LFL Distance (blue) = 115 m

***Figures 8a & 8b***

The figures depict the dispersion of motor spirit vapours, evaporated from the ETP section of the Storm Water Drain Network, under 1.5D weather conditions, with the wind from 20° East and West of North, in Figures a and b respectively. For the purpose of calculations, the storm water network was divided into discrete lengths, each of which could act as an independent source. The ETP section was considered to be 30 m long, 1 foot wide and 1.5 feet deep, with MS to half its depth. The distances from the point of the release are:

LFL Distance (blue) = 50 m

***Figure 9***

The figure depicts the explosion of motor spirit vapours, released by a tank roof failure, on account of pressurization of the tank by the dyke fire. The distances from the epicenter of the explosion are:

5 psi (blue) = 189 m

3 psi (yellow) = 258 m

2 psi (green) = 333 m

1 psi (red) = 528 m

***Figure 10***

The figure depicts the explosion of motor spirit vapours, spilt over 426 s. ***i.e.*** 7 min. 2 sec. (the time required for the cloud to stabilise), by a hammer blind assembly failure, under 1.5D weather conditions, with the wind from 20° East of North and the DG Set acting as the source of ignition. The distances from the epicentre of the explosion are:

5 psi (blue) = 77 m

3 psi (yellow) = 105 m

2 psi (green) = 135 m

1 psi (red) = 215 m

***Figure 11***

The figure depicts the explosion of motor spirit vapours, spilt over 426 s. (the time required for the cloud to stabilise), by a hammer blind assembly failure, under 1.5D weather conditions, with the wind from 20° East of North. This figure considers a source of ignition close to the source of the release just beyond the Upper Flammability Limit. The distances from the epicentre of the explosion are:

5 psi (blue) = 77 m

3 psi (yellow) = 105 m
2 psi (green) = 135 m
1 psi (red) = 215 m

***Figure 12a & 12b***

Each of the figures, depicts the vertical jet that could arise from a hammer blind assembly failure, under 1.5D weather conditions, but at different angles. While 13a depicts the jet at 10° from the vertical, 13b depicts the jet at 20° from the vertical. The heights and distances reached by the jets are given below:

Jet at 10° from the vertical:

Horizontal distance covered = 6 m (approximately)
Height of jet = 11 m (approximately)

Jet at 20° from the vertical:

Horizontal distance covered = 10 m (approximately)
Height of jet = 10 m (approximately)

Since the tank bund was about 10 m from the hammer blind assembly, the motor spirit released may have spilled over the bund, in addition to flooding the area within it.

Figure 1a Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Model: Line Rupture Wind from: 20° East of North

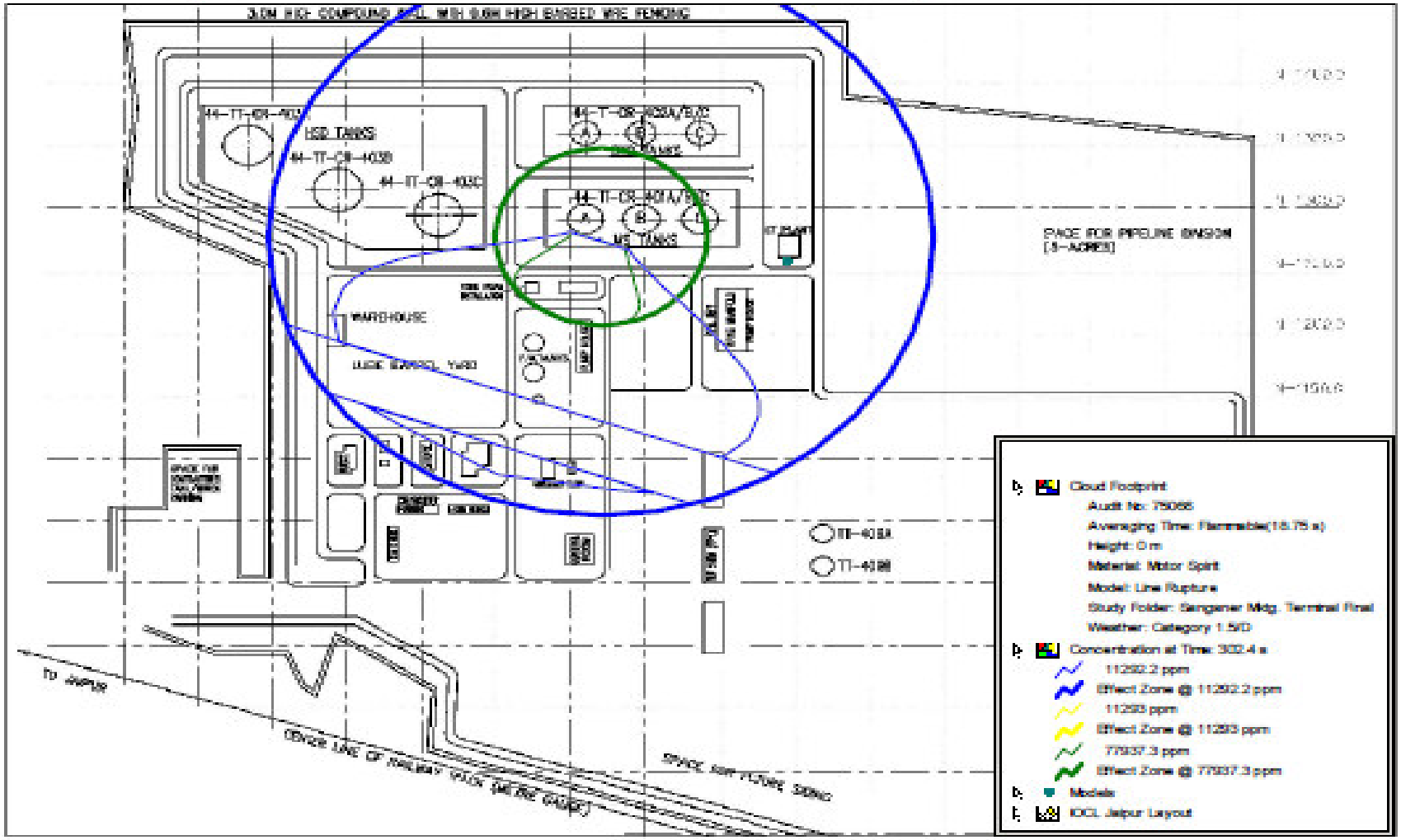

Figure 1b Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Model: Line Rupture Wind from: 20° West of North

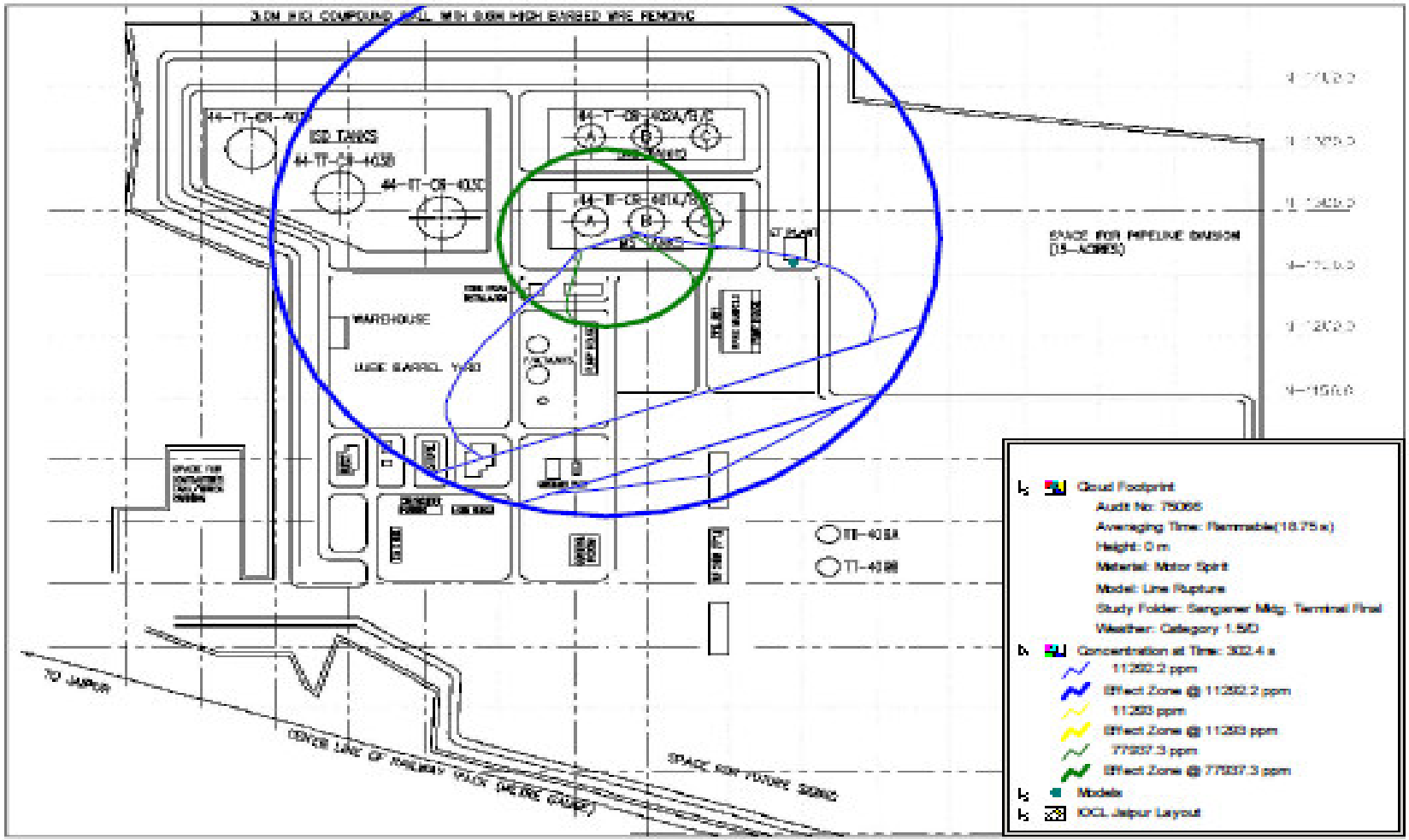

Figure 2a Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Model: Hammer Blind Assembly Failure Wind from: 30° East of North

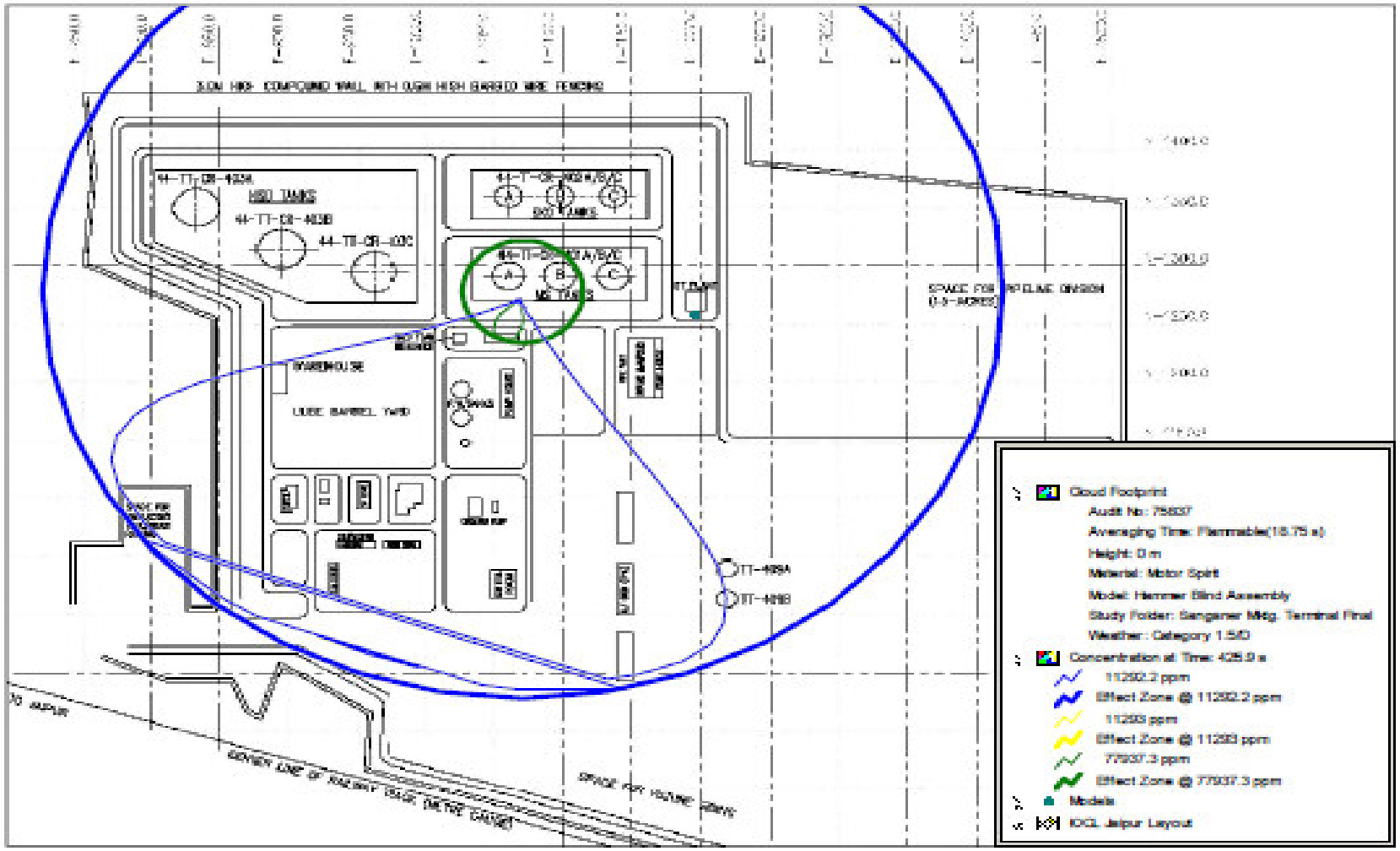

Figure 25 Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Model: Hammer Blind Assembly Failure Wind from: 20° West of North

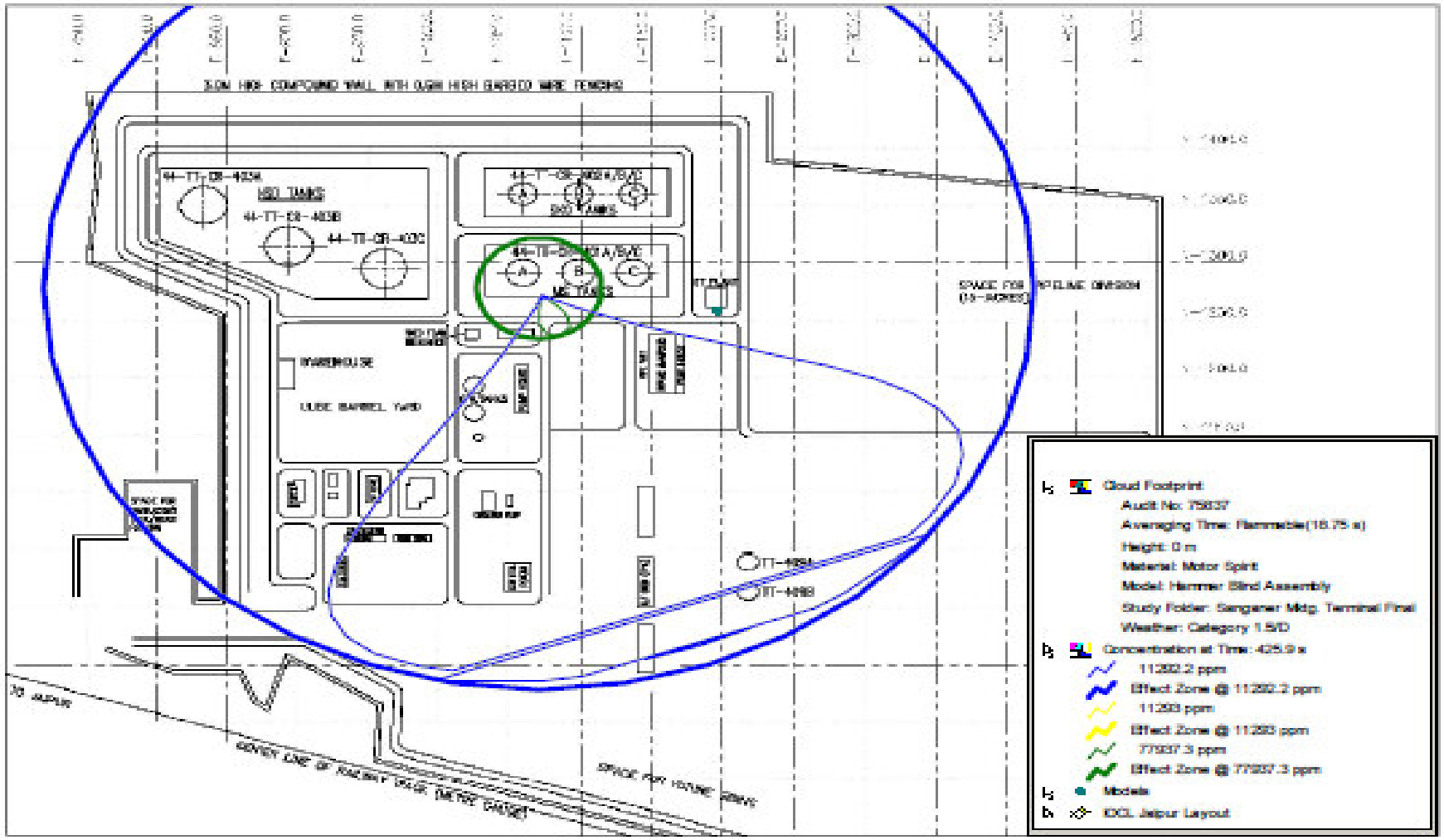

Figure 3 Explosion Overpressure Contours Weather Conditions: 1.5 D Source of Ignition: DG Set

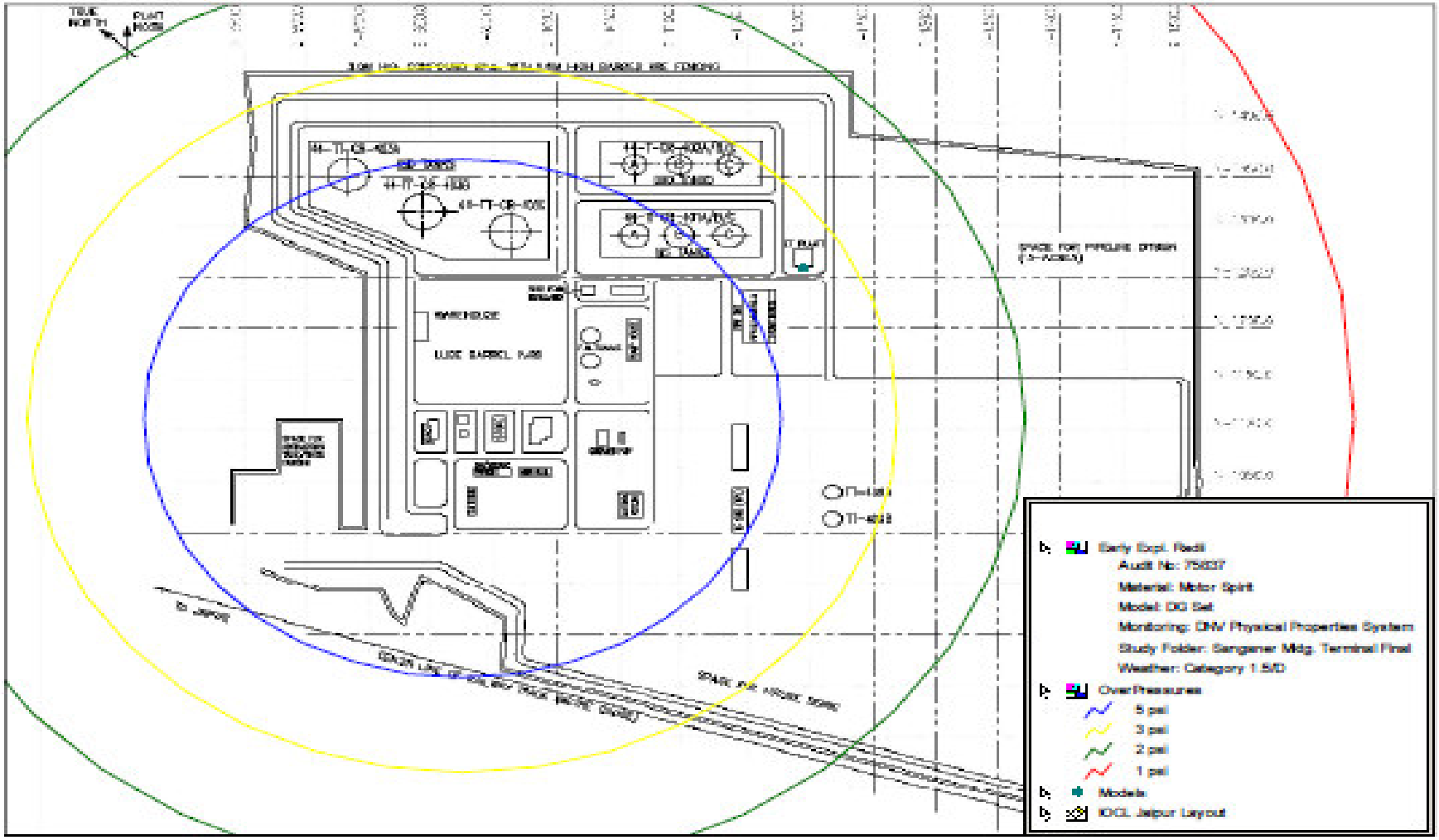

Figure 4 Explosion Overpressure Contours Weather Conditions: 1.5 D Source of Ignition: Motor-cycle

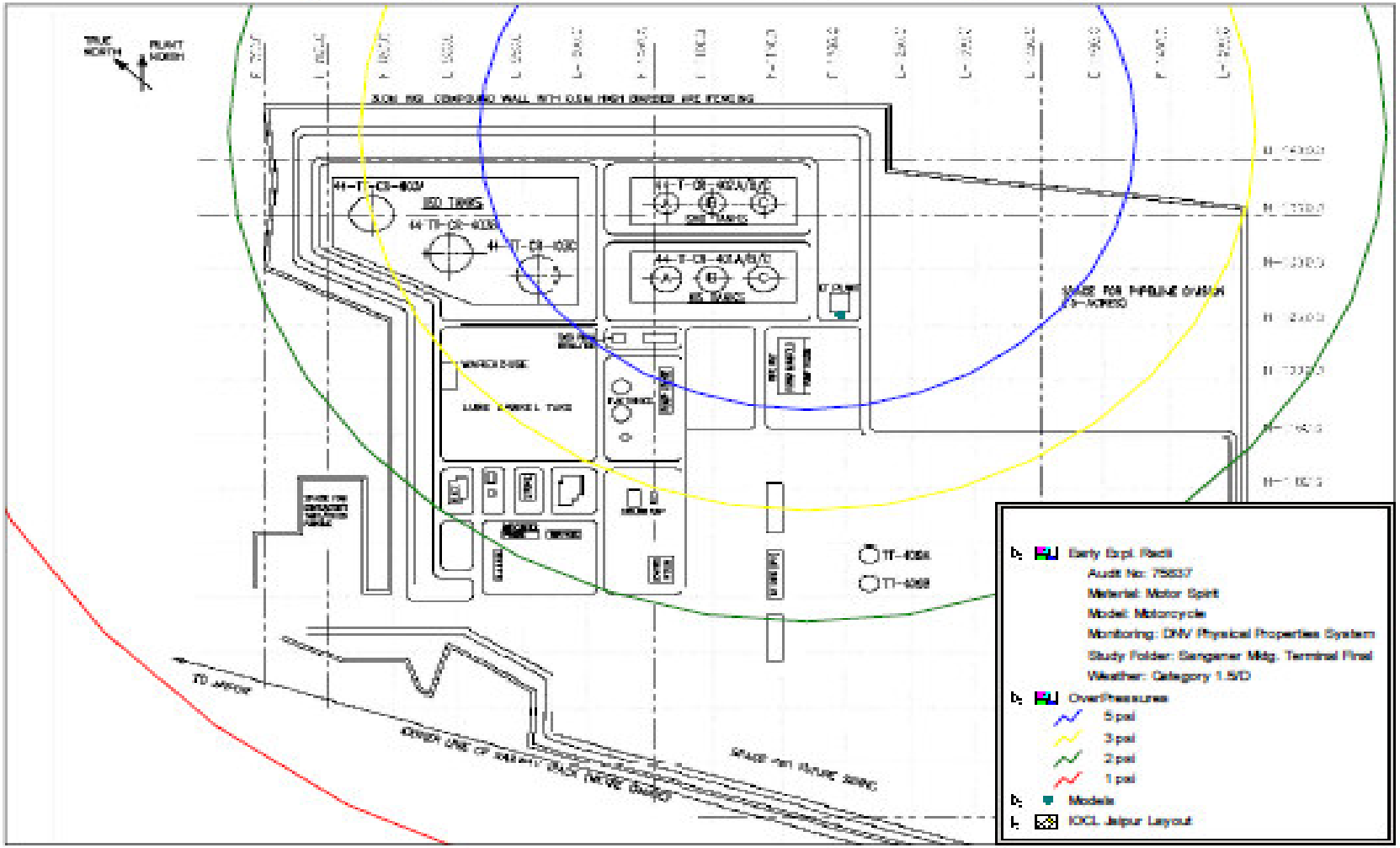

Figure 5 Explosion Overpressure Contours Weather Conditions: 1.5 D Source of Ignition: Jeep

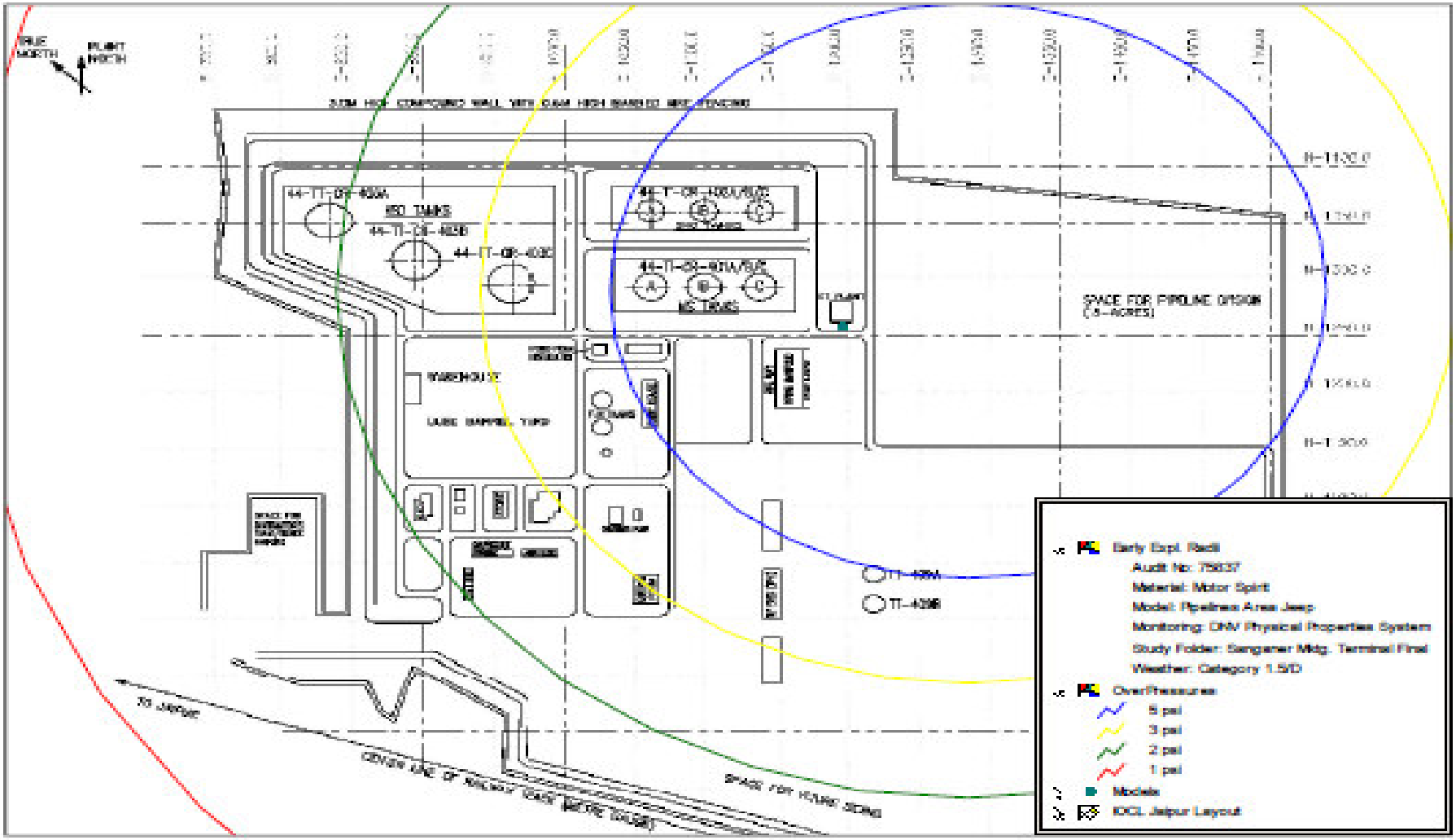

Figure 6 Dyke Fire Radiation Distances Weather Conditions: 1.5 D Model: Hammer Blind Assembly Failure

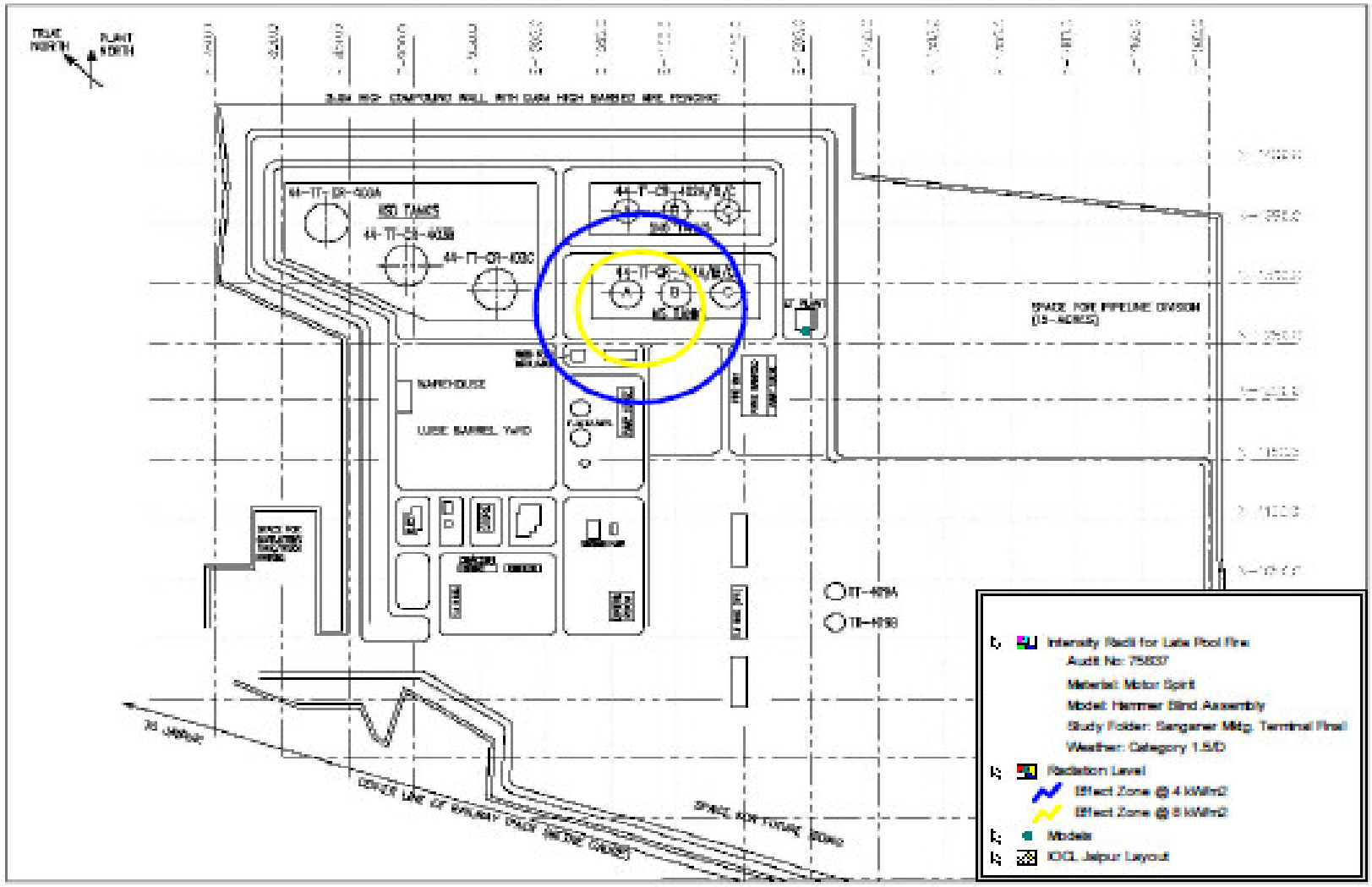

Figure 7a Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Source: MS Tank Farm E-W Drain Wind from: 20° East of North

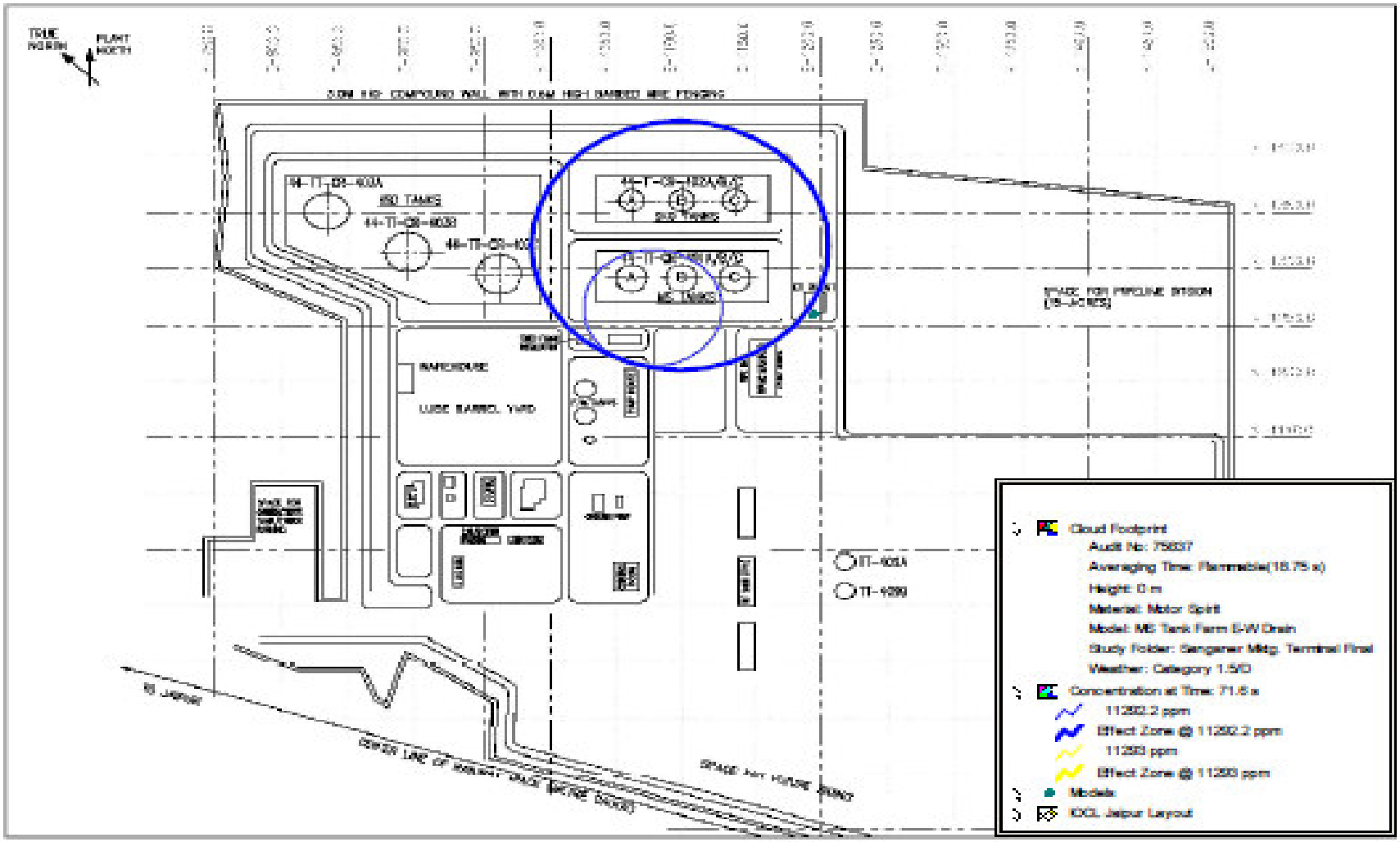

Figure 7b Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Source: MS Tank Farm E-W Drain Wind from: 20° West of North

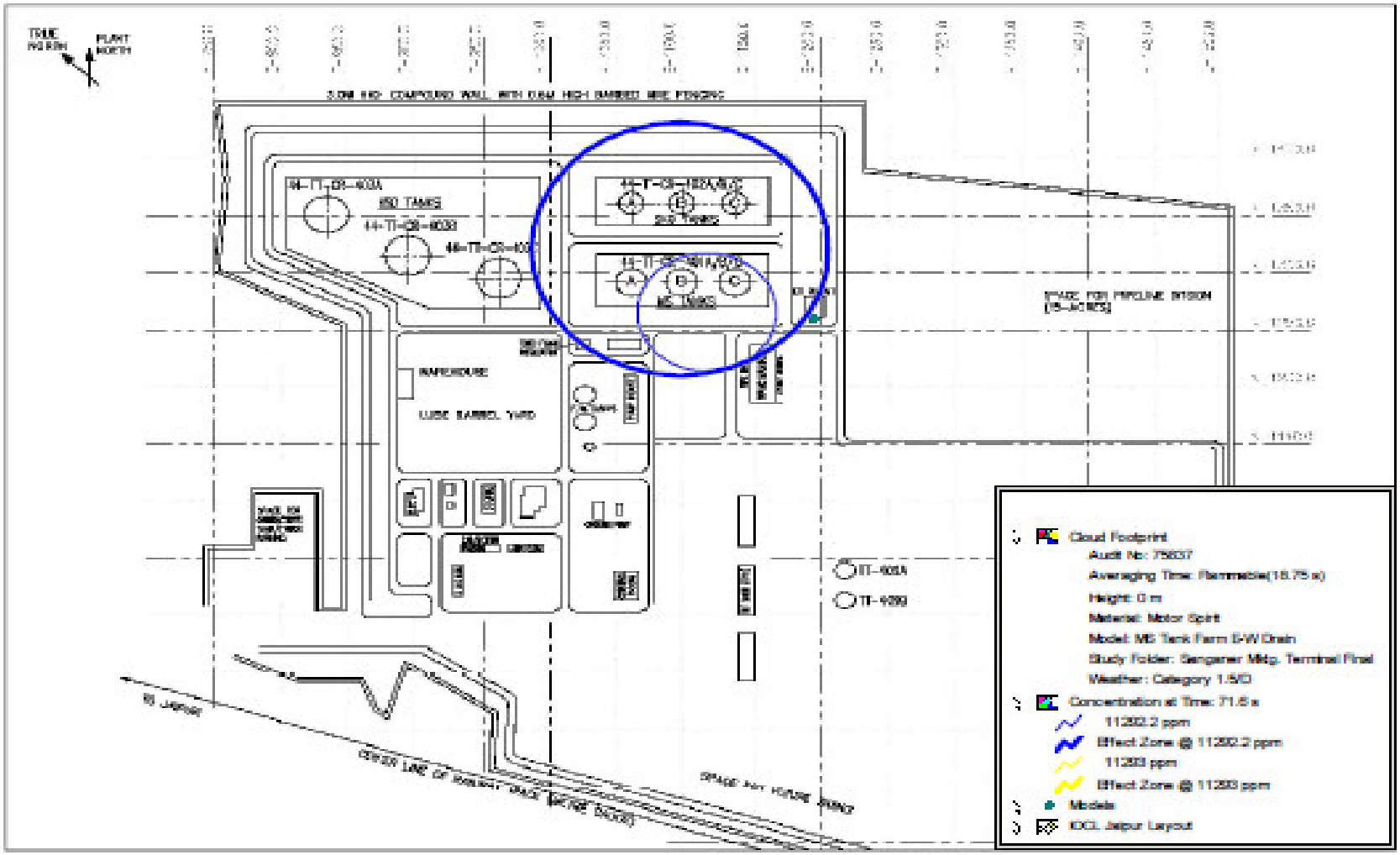

Figure 8a Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Source: ETP Drain Wind from: 20° East of North

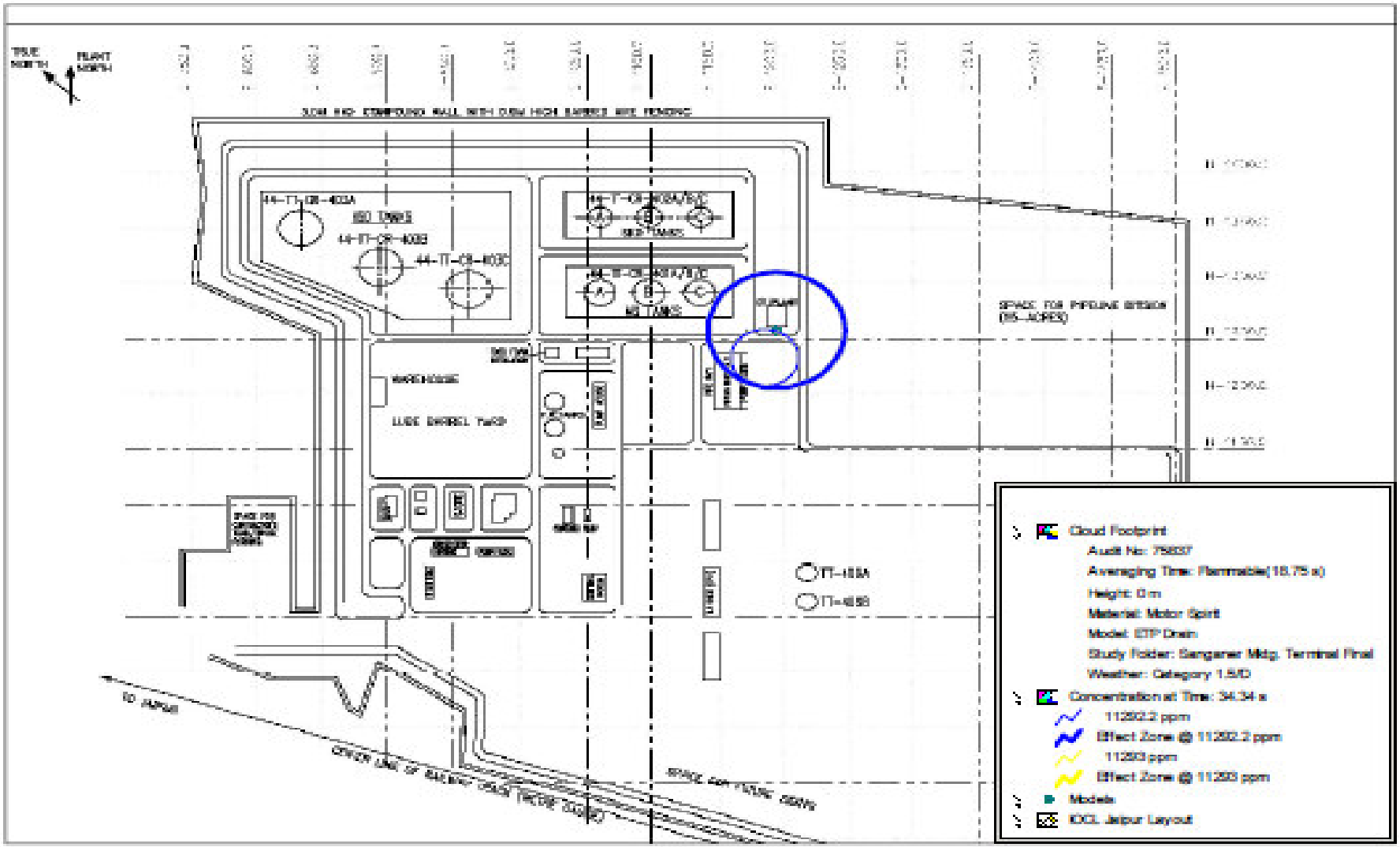

Figure 8b Dispersion of Motor Spirit Vapours Weather Conditions: 1.5 D Source: ETP Drain Wind from: 20° West of North

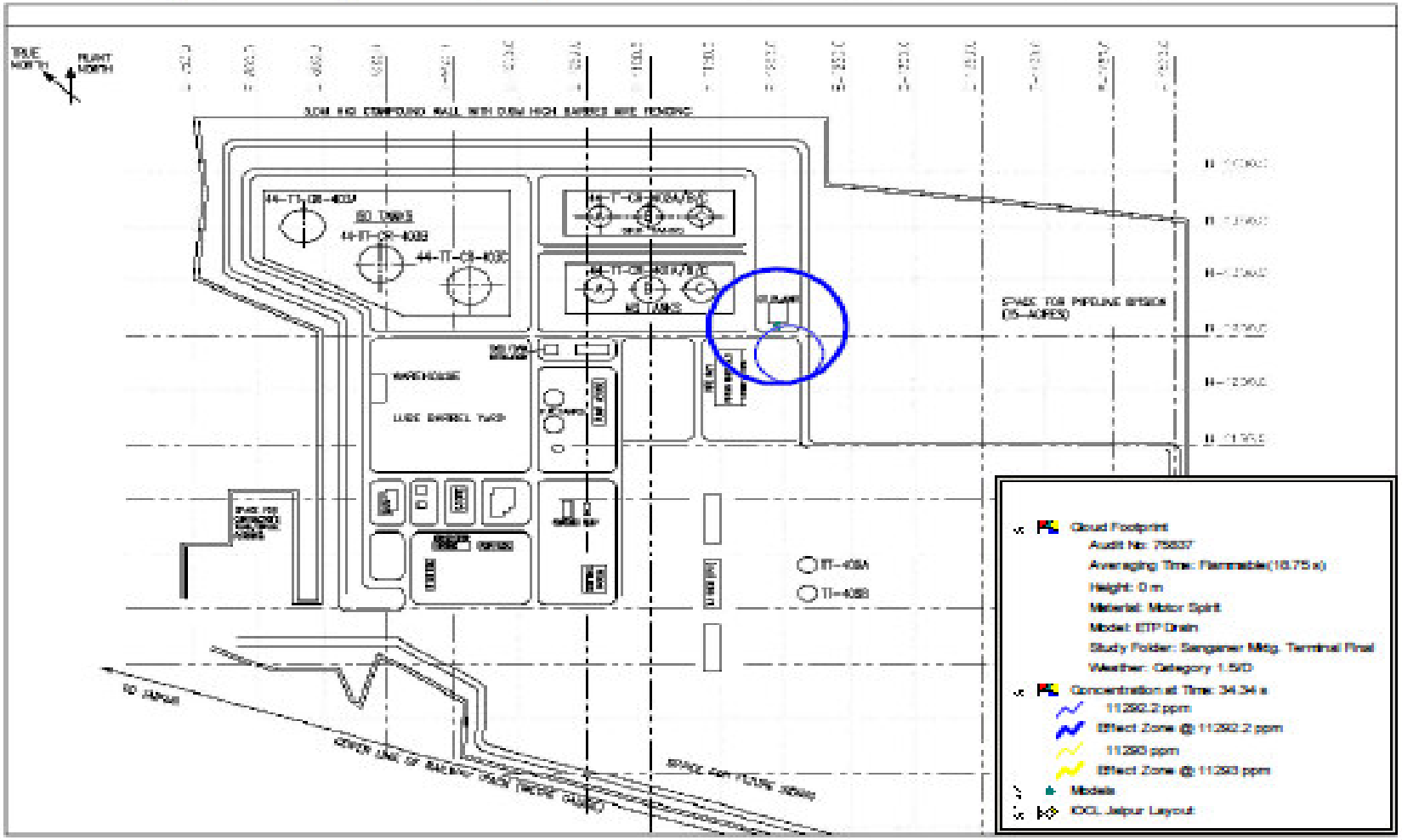

Figure 9 Possible Location of a Secondary Explosion Scenario – Tank roof Failure

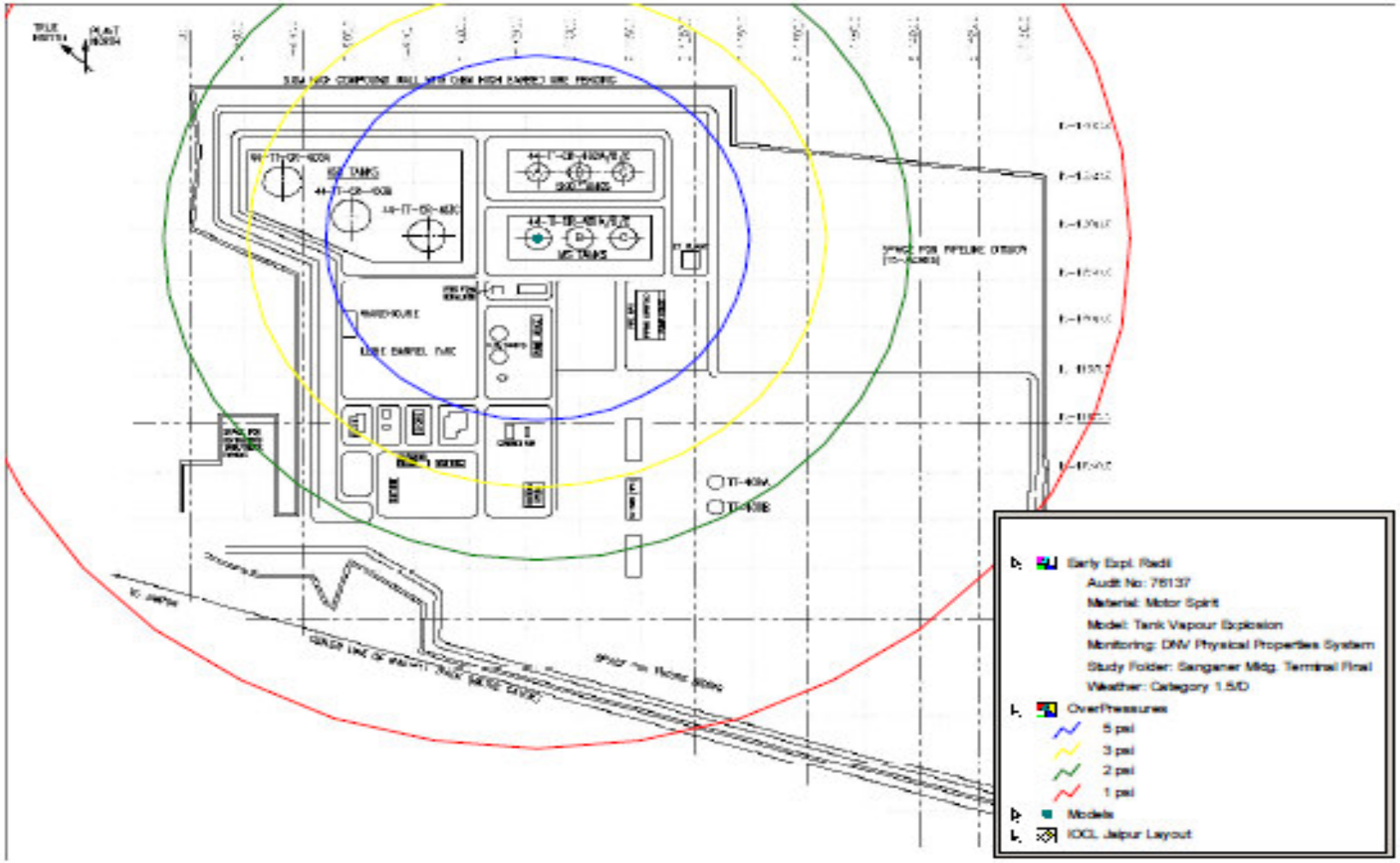

Figure 10 Explosion Overpressure Contours Weather Conditions: 1.5 D Source of Ignition: DG Set

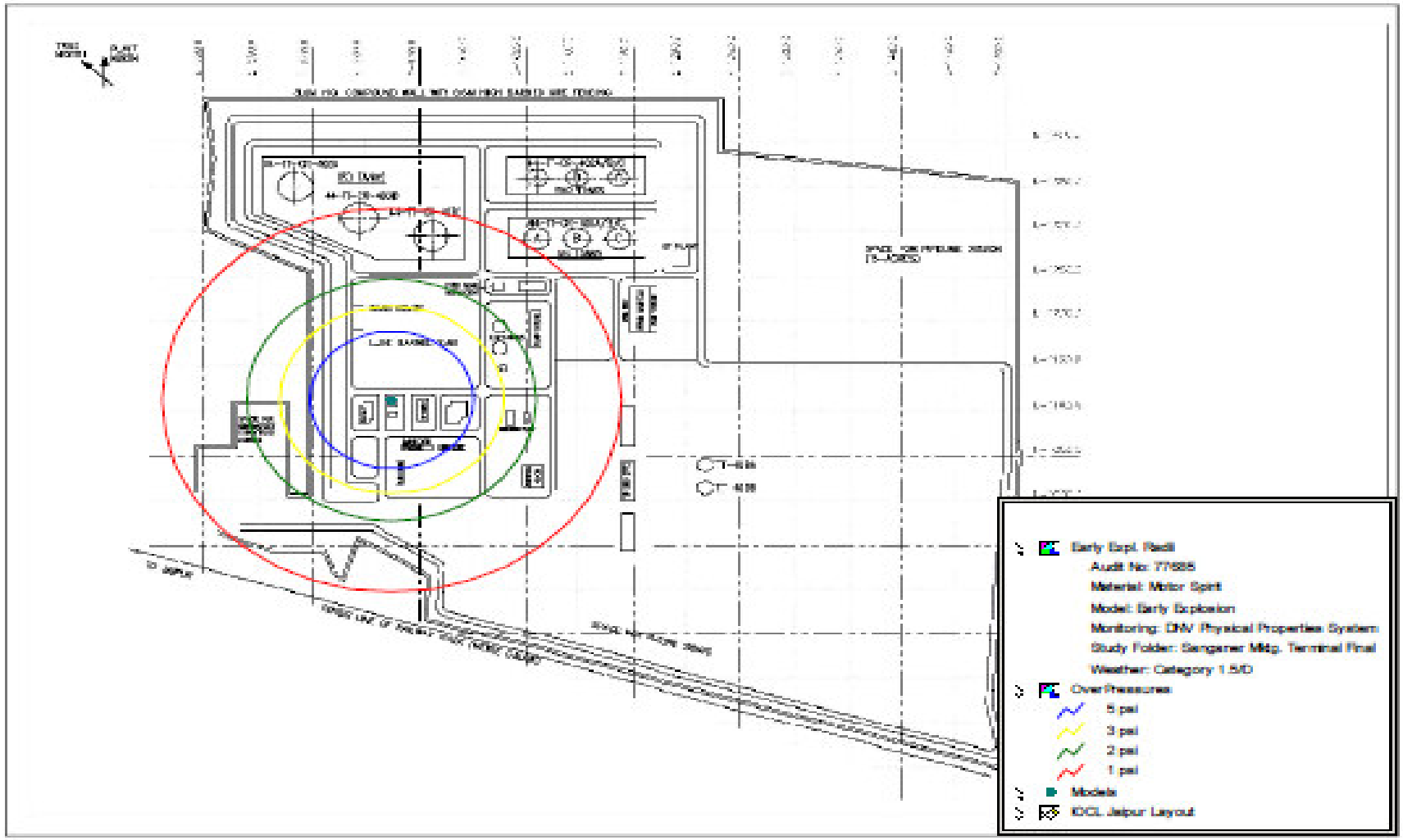

Figure 11 Early Explosion Overpressure Contours Weather Conditions: 1.5 D

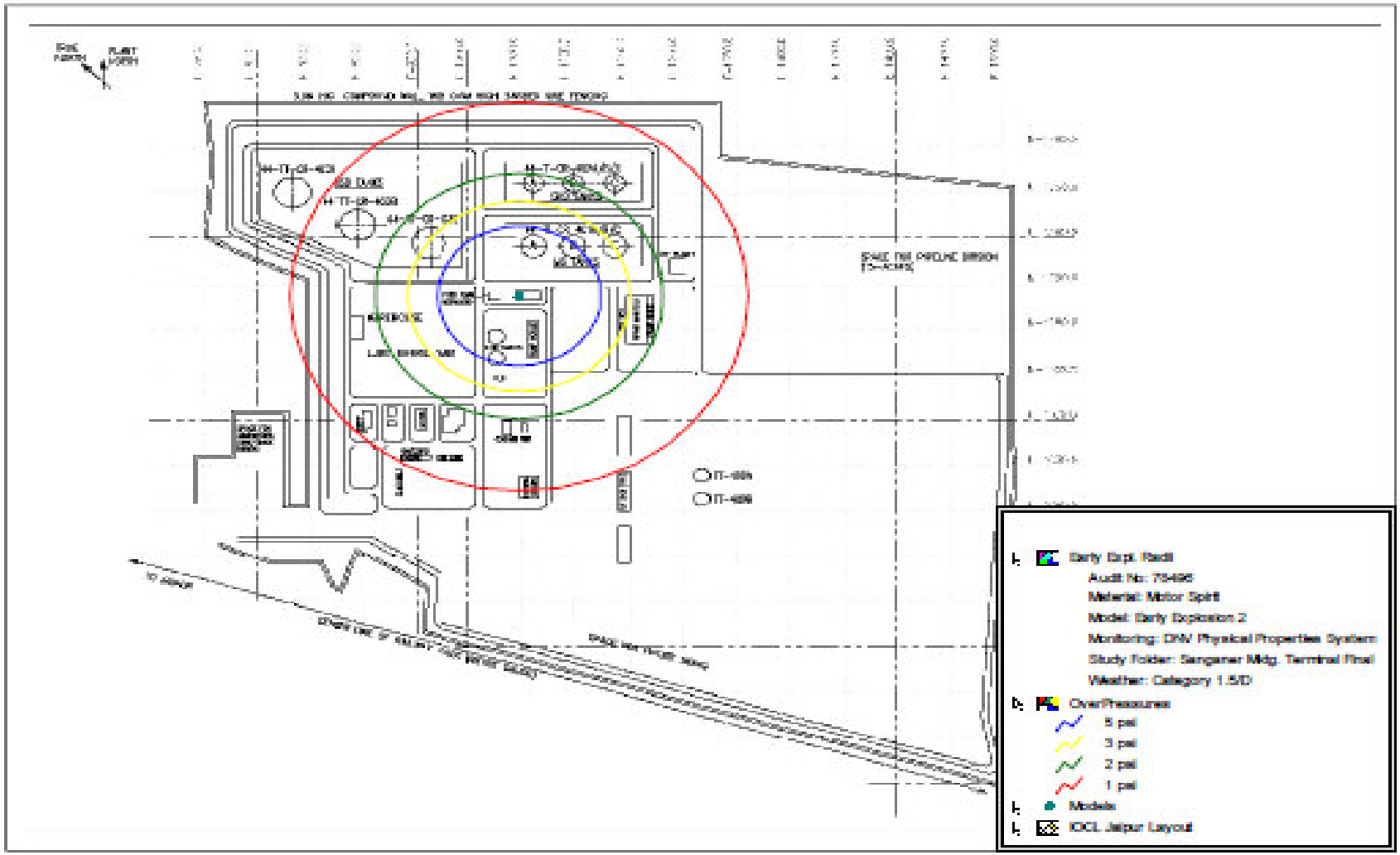

Figure 12a Jet Distribution under 1.5D Weather Conditions Angle of Release: 10° from the vertical

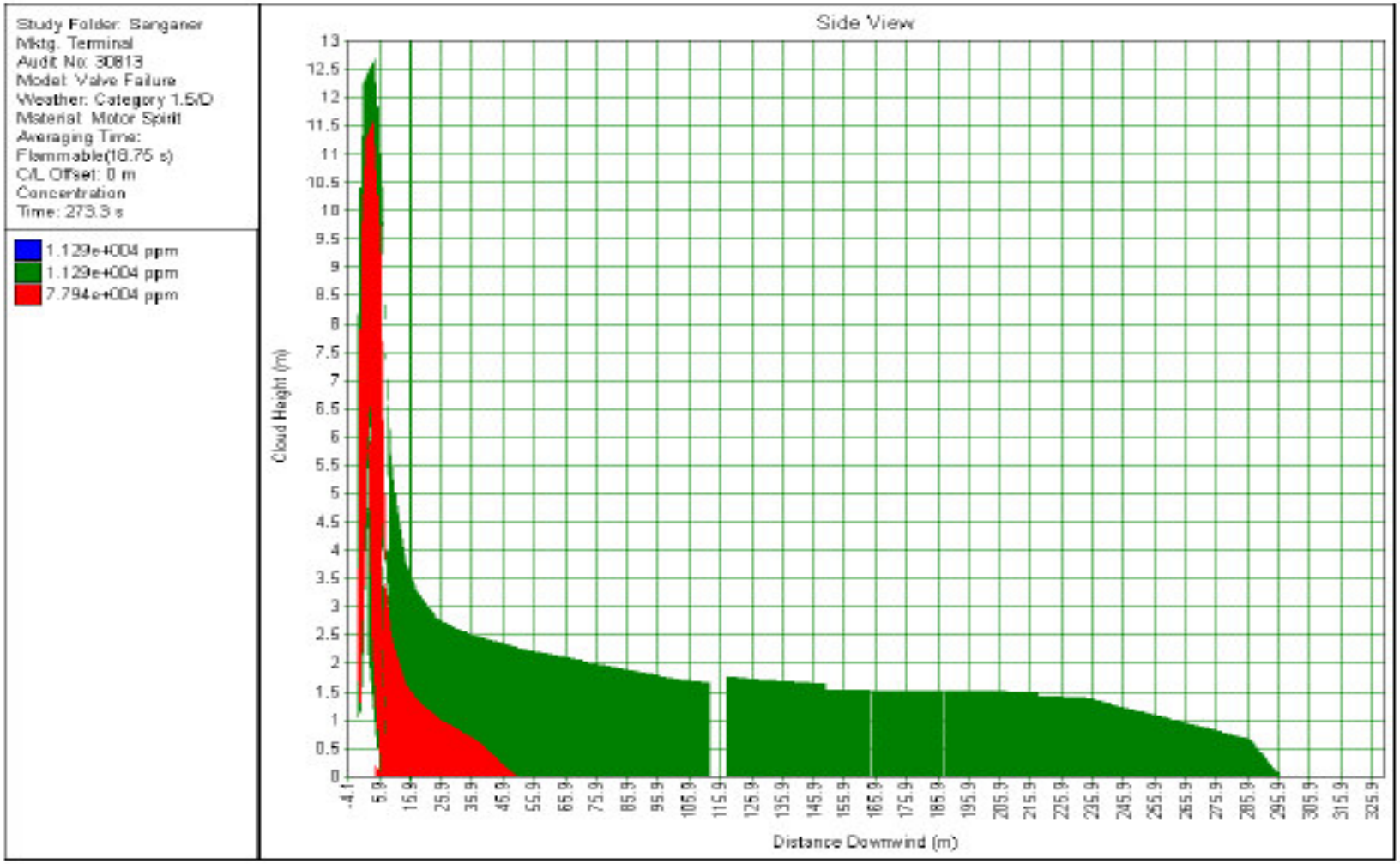
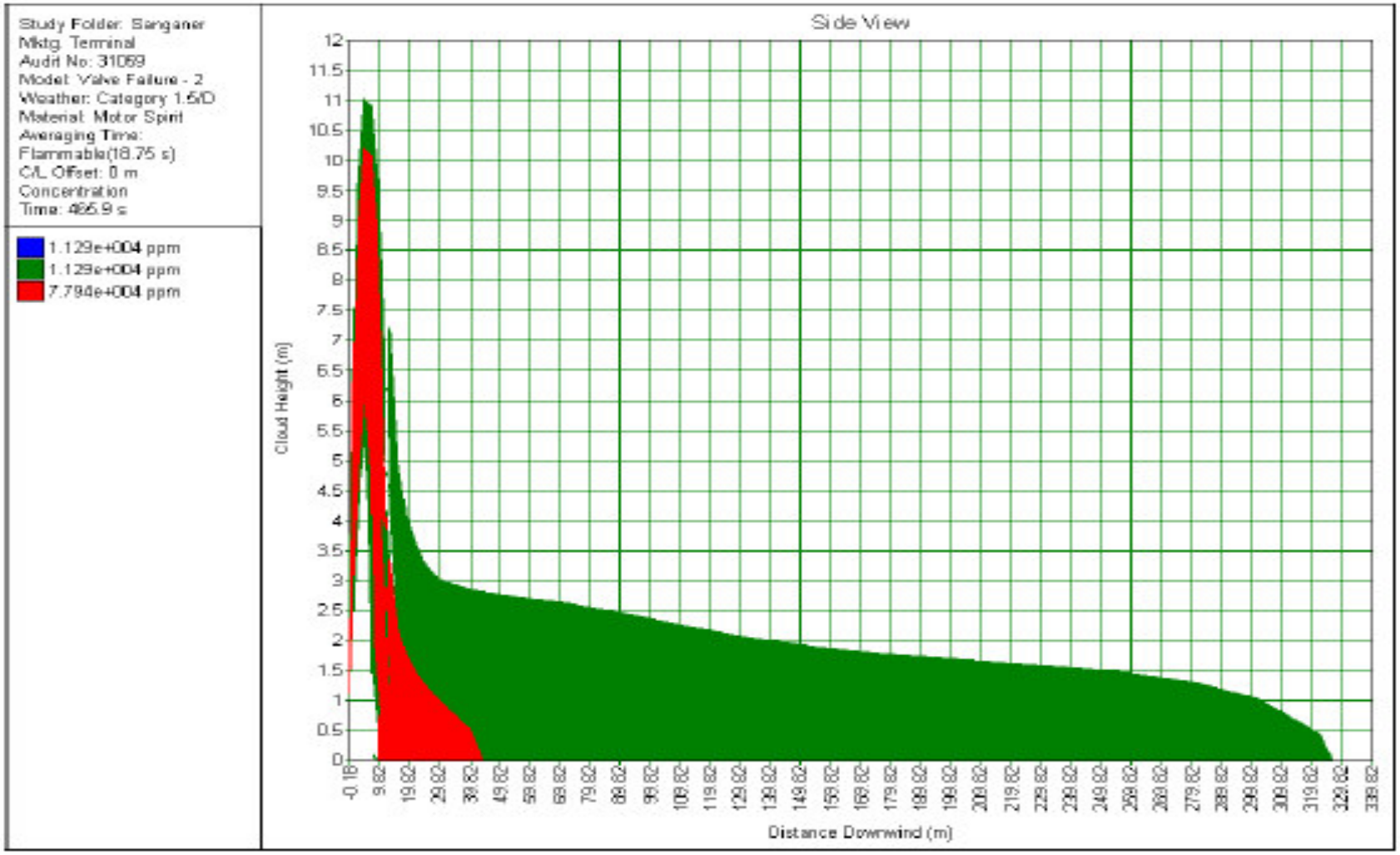
Figure 12b Jet Distribution under 1.5 D Weather Conditions Angle of Release: 20° from the vertical