THERMAL RADIATION FROM FIREBALLS ON FAILURE OF LIQUEFIED PETROLEUM GAS STORAGE VESSELS

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Fire impingement on vessels containing pressure liquefied gases can result in catastrophic failure of the vessel resulting in a Boiling Liquid Expanding Vapour Explosion (BLEVE). If the gas is flammable, this can result in the formation of very large fireballs. In safety assessments where catastrophic vessel failure is identified as a real possibility, the risk of death from a fireball tends to be higher than that from missiles or blast.

Since many of the physical processes which take place in a BLEVE are scale dependent, a series of tests were undertaken at a large scale where 2 tonne propane vessels were taken to failure in a jet fire and the vessel response, mode of failure and consequences of failure characterised. The measurements taken by the Health and Safety Laboratory and BG Technology relating to fireball formation are described.

Keywords: fireball, propane, LPG, BLEVE, thermal radiation, jet fire.

INTRODUCTION

Within the petrochemical industries, many flammable gases are stored as liquids under pressure. To ensure safe working practices, safety assessments are undertaken to consider the hazards posed by accidental releases from such storage vessels in order to assess the risk presented to the installation, personnel and the local population. Hence, a wide range of release scenarios needs to be considered, including those of low probability but with high consequential hazard, such as catastrophic failure. One such scenario, which may give rise to failure, is jet-flame impingement onto the storage vessel, perhaps resulting from an ignited release from a leaking flange or failed pipework. Such fires can result in catastrophic consequences e.g. the Mexico City disaster[1].

Fire impingement on a vessel containing pressure liquefied gas causes the pressure to rise within the vessel and the vessel wall to weaken and may ultimately lead to catastrophic failure and total loss of inventory. If such an event occurs, the liquefied gas is released to the atmosphere, where it boils and flashes back to its gaseous state because of the sudden reduction in pressure. The gaseous material expands to occupy a much greater volume than the liquid material and a pressure wave is generated. These types of events are known as Boiling Liquid Expanding Vapour Explosions (BLEVEs). If the released material is flammable, ignition is likely to occur so that in addition to missile and blast hazards, there is also a thermal radiation hazard from the fireball produced. It is the thermal radiation hazard which tends to dominate the near-field risk assessment[2].

Since many of the physical processes taking place in events such as BLEVEs are scale dependent, in order to gain an understanding of the hazard posed, it is necessary to conduct tests at a large scale. In 1989, a series of tests[3] were conducted as part of the Commission of the European Community (CEC) co-funded research initiative on Major Technological hazards. Seven tests were conducted to study the BLEVE failure of vessels containing up to 2 tonnes of either propane or butane. The effect of the different fuels, the vessel size, the vessel fill ratio and the pressure at failure were investigated. During these tests, the vessel contents were heated using an internal electric heater and failure of the vessels was initiated artificially using an explosive charge. The resulting missile throw, overpressures and fireball characteristics were investigated.

Following on from these experiments, also as part of the CEC Science and Technology for Environmental Protection (STEP) programme, a co-funded project was set up to investigate the hazard consequences of Jet-fire Interaction with VEssels containing pressurised liquids (JIVE). The Health and Safety Laboratory (HSL) was contracted by the CEC and HSE's Technology Division to investigate the thermal response of propane vessels when subjected to jet-fire attack and to assess the effectiveness of mitigation techniques. As part of this work, a series of four experiments were undertaken to look at the response of vessels up to the point of BLEVE failure and to gather some understanding of the mode of failure when a vessel is exposed to a real jet-fire impingement situation. BG Technology (BGT) were invited to make measurements of thermal radiation characteristics of any resulting fireball produced during these four tests. This paper describes the measurements made by HSL and BG Technology relating to the fireballs formed on catastrophic failure of the vessels. A brief comparison of the results with the normal empirical models used is also made.

EXPERIMENTAL ARRANGEMENT

JET FIRE

The jet-fire scenario considered was liquid discharge through a hole in an adjacent punctured vessel or damaged pipework. The jet-fire size and location was chosen so that the 4.5 m long by 1.2 m diameter target vessels were at least three quarters engulfed in fire and the effects of wind were minimised. The jet fire consisted of ignited, flashing, liquid propane at a flow rate of about 1.8 kg s^{-1} from a nozzle equivalent to a 12.7 mm diameter hole. The two tonne target vessels were placed at approximately the still-air lift-off position of the flames i.e. 4.5 m. The mean heat flux density around the vessels was 179 kW m^{-2}.

PROPANE VESSELS

Each two tonne vessel was fitted with a pressure relief valve (PRV), protected by thermal insulation during the trials, set to relieve at 17.24 barg. The vessels were instrumented with thermocouples in the liquid and vapour space and protected from direct flame impingement by 3 mm plates on the outside of the shell. Pressure transducers were fitted to take-offs from the liquid and vapour space. The target vessels were mounted on a frame resting on load cells so that the fuel mass could be monitored.

THERMAL RADIATION

Instrumentation was deployed by BG Technology to measure the thermal radiation characteristics of any resulting fireball. Medtherm wide angle, slow and fast response radiometers, Land slow response radiometers and International Research and Development wide angle, fast response radiometers (WIRD) were set up along radial lines (see Figure 1) around the vessel to measure the incident thermal radiation at different distances from the fireball. An Agema 900 Infrared Thermal Imaging System (AGEMA) was used to record the surface emissive power distribution of the fireball throughout its duration. An International Research and Development narrow angle, fast response radiometer (NIRD), with a total field of view of 1°, was also deployed alongside the AGEMA. HSL used a LAND CYCLOPS Ti35sm thermal imaging camera, at approximately 90^o from the BGT camera, to measure the thermal image of the fireballs. The HSL thermal imaging camera viewed crosswind and the BGT camera viewed up or downwind. A sonic anemometer was deployed to measure the wind speed and direction.

FAILURE MODE TRIALS

INITIAL CONDITIONS

Four unprotected vessels, containing different quantities of propane (20%, 41%, 60% and 85% of the water capacity), were engulfed in a jet fire until they failed. The ambient conditions, degree of fill and mass flow rate of the propane jet used are summarised in Table 1. Normally the vessels were unrestrained but, because rocketing occurred in the 60% full vessel trial, the 85% full vessel was restrained.

Table 1. CONDITIONS FOR FAILURE MODE TRIALS

Degree of fill (%)	**20**	**41**	**60**	**85**
Propane mass (kg)	455	929	1,364	1,932
Propane jet mass flow rate ($kg.s^{-1}$)	1.5	1.4	1.6	1.7
Ambient temperature (^oC)	19	20	17	18
Wind direction relative to direction of jet (deg.)	180	180	0	180
Approximate wind speed ($m\ s^{-1}$)	4	3	5	2.5
Relative humidity (%)	80	60	95	90

GENERAL OBSERVATIONS

In each trial, propane was immediately ignited by a pilot light when ejected from the nozzle. It burnt with a bright yellow flame that became slightly darker as the proportion of liquid ejected increased. This gave a flame that almost enveloped the target vessel but, occasionally, the left side (in relation to the jet) of the vessel could be seen indicating that the flames were slightly skewed to the right. After 1 to 2 minutes, the PRV opened releasing gas that ignited to give a jet of flame. All the vessels failed catastrophically within about 3 minutes of the PRV opening giving a large fireball. On failure, three vessels split longitudinally and opened out flat and the other (60%), after initially splitting longitudinally, split circumferentially and rocketed.

CONDITIONS AT FAILURE

All the vessels failed within 5 minutes of commencing jet-fire impingement and at pressures ranging from 16.5 to 24.4 barg. In all cases except for the 20% full vessel, after the initial pressure drop on PRV opening, the pressure increased until, at failure, the pressure was higher than the respective initial PRV opening pressure. For the 20% full vessel, the pressure fell from 18.6 barg to 16.5 barg.

There was considerable variation in the vessel wall temperatures depending on whether the wall was in contact with liquid propane or not. In every trial, the wall temperature just above the liquid level was much higher than that just below the liquid level suggesting that there was relatively little level swell with consequent cooling of the wetted wall. The temperatures at the back were lower than those at the front except for the 60% full vessel trial, which was the only trial in which the wind was in the same direction as the jet. In all cases, the wall in contact with the vapour space reached the highest temperatures. The pressures and highest shell temperatures at the time of failure are summarised in Table 2.

Table 2. PRESSURE AND HIGHEST SHELL TEMPERATURE AT FAILURE

Degree of fill (%)	Failure time (s)	Pressure (bar g)	Highest shell temperature (Celsius)
20	250	16.5	870
41	286	21.3	704
60	217	18.6	821
85	254	24.4	848

PARAMETERS AFFECTING FIREBALL FORMATION

When the target vessels failed, the contents were released very rapidly. As the temperature of liquefied propane was at least 100 ^{o}C higher than its boiling point (- 42 ^{o}C) at atmospheric pressure, it rapidly boiled with a considerable proportion of the liquid immediately flashing to vapour on loss of containment, giving a BLEVE. In every case, the vapour clouds ignited almost immediately giving large fireballs. The parameters affecting fireball formation are summarised in Table 3.

Table 3. PARAMETERS AFFECTING FIREBALL FORMATION

Fill percentage (%)	Propane released (kg)	Wind speed (m s^{-1})	Wind direction	Tank failure mode
20	279	3	Westerly	Opened out flat
41	710	4	Westerly	Opened out flat
60	1,272	5	South-easterly	Split circumferentially
85	1,708	2	Westerly	Opened out flat

THERMAL RADIATION MEASUREMENTS

The fireball from each trial is shown at its maximum size in Figure 2. Table 4 shows a summary of the incident thermal radiation results (Medtherm radiometers along lines A and C) from the 85% full vessel trial and Figure 3 shows the thermal images of fireball growth during this trial. The variation of incident thermal radiation received at 100 m is illustrated in Figure 4 and the dosage against distance in Figure 5. In general, there was good agreement between the results from the narrow angle radiometer and the AGEMA, with the AGEMA giving values within 10% of those of the NIRD. Because of cloud drift, the crosswind (line C) results are higher than the upwind (line A) results.

Table 4. INCIDENT THERMAL RADIATION AND DOSAGE DATA (85% TRIAL)

Distance (m)	Line A (upwind)		Line C (crosswind	
	Maximum radiation (kW m^{-2})	Dosage (kJ m^{-2})	Maximum radiation (kW m^{-2})	Dosage (kJ m^{-2})
50	36.72	132.00	47.78	169.12
75	20.03	81.08	28.13	114.75
100	14.03	55.47	18.12	73.73
125	9.70	37.65	11.96	49.98
150	8.03	28.68	9.51	36.99
200	4.38	16.56	5.05	21.27

The fireball dimensions and surface emissive power data, measured at maximum projected area, are summarised in Table 5. There is some uncertainty in the durations given as the fireball breaks up into small flame eddies just before extinction and there are different perceptions of extinction. The flame heights and widths are calculated from the number of pixels, the pixel size, the distance of the camera from the fireball and the field of view of the camera lens. The error in the surface emissive powers is estimated to be ± 15% and errors in dimensions to be ± 5%.

Table 5. FIREBALL DATA AT MAXIMUM PROJECTED AREA

Trial		**20%**	**41%**	**60%**	**85%**
Propane released (kg)		**279**	**710**	**1,272**	**1,708**
Cross or up/downwind	**View**				
Duration (s)	CW	3	5	6.5	7
	U/D	3.8	4.6	5.9	6.6
Time to maximum power (s)	CW	1.56	< 2	2.6	3.12
	U/D	1.38	2.07	3.04	2.96
Time to maximum projected area (s)	CW	2.08	2	3.12	3.64
	U/D	2.21	2.84	4.18	3.69
Area at maximum power (m^2)	CW[a]	1221	< 2040	2907	4244
	U/D[b]	837	1406	3176	3267
Maximum projected area (m^2)	CW[a]	1300	2040	3150	4600
	U/D[b]	960	1460	3840	3520
Height (m) (at maximum area)	CW	43	67	72	105
	U/D	42	59	98	103
Width (m) (at maximum area)	CW	45	41	65	85
	U/D	41	43	74[c]	71
Average SEP (kW m^{-2}) (at maximum power)	CW	403	> 195[d]	314	312
	U/D	294	242	245	285
Average SEP (kW m^{-2}) (at maximum area)	CW	295	> 195[d]	287	312
	U/D	188	196	117	212
Maximum average SEP (kW m^{-2})	CW	413 (1110 m^2)	> 195[d]	320 (2670 m^2)	360 (3210 m^2)
	U/D	333 (650 m^2)	278 (1060 m^2)	270 (2470 m^2)	314 (1860 m^2)
Maximum SEP (kW m^{-2})	CW[e]	650	> 195	482	556
	U/D[f]	554	484	486	523
Maximum power (MW)	CW	492	> 398	913	1451
	U/D	246	340	778	931

[a] 670 ^{o}C (cf. 45 kW m^{-2}) fireball contour used to define area
[b] 40 kW m^{-2} fireball contour used to define area
[c] Estimated width as flame outside AGEMA field of view
[d] Instrument not set for maximum range
[e] Point maximum
[f] 10% maximum

The data show that the maximum average surface emissive power occurs before the fireball reaches its maximum size. The variation of surface emissive power and projected area with time is illustrated for the 85% full vessel trial in Figures 6 and 7 respectively. In general, the maximum surface emissive powers measured crosswind were higher than those measured up/downwind. The average up/downwind surface emissive power, at maximum power, was in the range 242 to 294 kW m^{-2} and, at the maximum projected area, was 117 to 212 kW m^{-2}. The corresponding crosswind ranges were 312 to 403 kW m^{-2} and 295 to 312 kW m^{-2}, respectively. Both sets of results indicated that the highest average surface power was from the release of propane from the vessel with the lowest (20%) degree of fill and that failed at the lowest pressure.

DISCUSSION

The trials have confirmed that, when a BLEVE of a vessel containing flammable pressure liquefied gas occurs, the main effects are thermal radiation, fragmentation and blast. In terms of potential to kill, the thermal radiation from the large fireball formed is by far the most dominant hazard for personnel near to the vessel.

When the vessels fail, the rapid vaporisation and expansion results in a cloud of vapour and small droplets, with the concentration of vapour within the cloud being above the upper flammable limit. After ignition, turbulent burning occurs mainly from the outside inward. Burning of the vapours and droplets increases the buoyancy within the burning cloud and hence increases its tendency to rise. The volume of the fireball also increases. The turbulence maintains rapid mixing within the cloud and hence an increased rate of burning with high flame temperatures, little soot formation and the emission of higher levels of thermal radiation. The amount of thermal radiation emitted from the fireball depends, as a function of time, on the surface area and surface emissive power and, for a given size of fireball and surface emissive power, the radiation dosage received by a target will depend upon the distance from the source, atmospheric transmissivity and the fireball duration.

There have been numerous papers on evaluation of fireball hazards, some deriving empirical relationships, some theoretical relationships and some a combination of the two. In general, for the purposes of risk assessment, empirical relationships are used. Comparison of data obtained with published empirical models is restricted to HSL work[2&4] and to recent comprehensive reviews, with guidelines, published[5&6] by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers.

FIREBALL DURATION

Both Roberts[4] and the CCPS[6] suggest using the expression:

$$t = 0.45 \cdot M^{1/3} \qquad (M < 30{,}000 \text{ kg}) \qquad (1)$$

to calculate the time, t (s), when visible radiation from the fireball ceases from the released mass of fuel, M (kg). However, Prugh[7] suggests that the expression in the CCPS Guidelines for Chemical Process Quantitative Risk Analysis[5] be used viz.

$$t = 0.825 \cdot M^{0.26} \qquad (2)$$

The results are compared in Table 6. The expression suggested by Prugh[7] gives a slightly better fit to the data although both expressions appear to underestimate the duration of the largest fireball.

Table 6. MEASURED AND PREDICTED FIREBALL DURATIONS

Propane released (kg)	Predicted duration $0.45 . M^{1/3}$ (s)	Predicted duration $0.825 . M^{0.26}$ (s)	Measured duration Crosswind (s)	Measured duration Up/Downwind (s)
279	2.9	3.6	3	3.8
710	4	4.5	5	4.6
1,272	4.9	5.3	6.5	5.9
1,708	5.4	5.7	7	6.6

FIREBALL DIAMETER

Although the shape of the fireball formed on vessel failure depends on the failure mode, fireballs are usually considered to be spherical in shape and for which a representative diameter can be calculated. Both Roberts[4] and the CCPS[6] suggest using the expression:

$$D = 5.8 . M^{1/3} \tag{3}$$

to calculate the maximum fireball diameter, D (m), from the mass of fuel, M (kg), released. Again Prugh[7] suggests that the expression in the CCPS Guidelines[5] be used viz.

$$D = 6.48 . M^{0.325} \tag{4}$$

The results are compared in Table 7. Again the marginally higher values given by the expression suggested by Prugh gives a slightly better fit.

Table 7. MEASURED AND PREDICTED FIREBALL DIAMETERS

Propane released (kg)	Predicted diameter $5.8 . M^{1/3}$ (m)	Predicted diameter $6.48 . M^{0.325}$ (m)	Measured diameter Crosswind (m)	Measured diameter Up/Downwind (m)
279	38	40	45	41
710	52	55	45	43
1,272	63	66	75	74
1,708	69	73	85	71

FIREBALL LIFT-OFF TIME AND ELEVATION

In general, hazard calculations assume that fireballs are spherical and touch the ground. In practice, the fireballs start to lift off when buoyancy and entrainment are dominant and drift with wind. Both Roberts[4] and the CCPS[6] recommend using the Hardee and Lee[8] expression for lift-off time, t_{lo} (s)

$$t_{lo} = 1.1 . M^{1/6} \tag{5}$$

Prugh suggests using the CCPS[5] expression for the height, H (m), of the centre of the fireball above the ground at the time of maximum diameter, D (m):

$$H = 0.75 \cdot D \tag{6}$$

The results, with D as predicted by Equation 4, are compared in Table 8.

Table 8. PREDICTED AND MEASURED LIFT-OFF TIMES AND ELEVATIONS

Propane released (kg)	Lift-off time		Elevation	
	$1.1 \cdot M^{1/6}$ (s)	Measured (s)	0.75 . D (m)	Measured (m)
279	2.8	2.2	30	22
710	3.3	3	41	33
1,272	3.6	3.4	50	31.5
1,708	3.8	3.7	55	49

SURFACE EMISSIVE POWER AND FIREBALL RADIATION

The radiation received by a target is usually calculated using either a point-source model or a solid-flame model.

Point source model: In the point-source model, it is assumed that a certain fraction (F) of the heat of combustion is radiated in all directions. Prugh suggests using the CCPS[5] relationship between the surface emissive power, SEP ($kW.m^{-2}$), heat of combustion, H_c ($J.g^{-1}$) and the fuel mass, M (kg) :

$$SEP = F \cdot M \cdot H_c / [\pi \cdot D^2 \cdot t] \tag{7}$$

If the expressions (Equations 2 and 4) for D and t are substituted and the heat of combustion of propane is taken as 46,000 $J\ g^{-1}$ then this expression reduces to:

$$SEP = 423.2 \cdot F \cdot M^{0.09} \tag{8}$$

Prugh gives an example where F is taken as 0.25 for propane. Roberts suggests that the radiation fraction is related to the pressure, P (MPa), by the expression:

$$F = 0.27 \cdot P^{0.32} \qquad (P < 6\ \text{MPa}) \tag{9}$$

F is usually taken to be in the range 0.25 to 0.40. Roberts' expression is not derived from the same data set as Prugh and, strictly speaking, should only be used with corresponding expression derived from the original data. The calculated values, using Prugh's expression, are compared with the average values at maximum projected area in Table 9.

Table 9. PREDICTED AND MEASURED SURFACE EMISSIVE POWERS

Amount of propane released (kg)	Pressure at failure (MPa)	Fraction radiated $F = 0.27 . P^{0.32}$	Calculated SEP = $423.2 . F. M^{0.09}$		Average SEP at maximum area	
			F = 0.25 (kW m^{-2})	F = 0.40 (kW m^{-2})	Crosswind (kW m^{-2})	U/D wind (kW m^{-2})
279	1.65	0.32	176	281	295	188
710	2.13	0.34	191	306	> 195	196
1,272	1.86	0.33	201	322	287	117
1,708	2.44	0.36	207	331	312	212

Nearly all the data is covered by the radiated fraction range of 0.25 to 0.40. However, it should be noted that the upwind and downwind average surface emissive powers at maximum output, are in the range 242 to 294 kW m^{-2} ,i.e. much higher than at maximum projected area, and that it could be misleading to use the values at maximum projected area. In general, the measured average surface emissive power is only near its maximum value for about 50% of the fireball duration. The CCPS[6] suggest that a reasonable value for the surface emissive power associated with large scale releases of hydrocarbon fuels is 350 kW m^{-2}. Currently, a value of 270 kW m^{-2} is utilised in LPG RISKAT[2]. British Gas[3] measured surface emissive powers of 320 to 370 kW m^{-2} from 1000 and 2000 kg releases of butane and propane at 0.75 and 1.5 MPa.

Solid-flame model: In the solid-flame model, the radiation received is calculated from the surface emissive power (SEP, kW.m^{-2}) of the flames, the relative geometry of the target and fireball and the atmospheric attenuation. The incident radiation, I (kW m^{-2}) is given by:

$$I = V . SEP . \tau \qquad (10)$$

where V is the view factor and τ the atmospheric transmissivity.

The solid-flame model is more realistic than the point source model, particularly for distances less than five fireball diameters away. However, the view factor calculations are more complicated and the atmospheric conditions need to be known if a reasonable atmospheric attenuation model is to be used.

CONCLUSIONS

The following conclusions are drawn:

- The resulting size and shape of the fireball following the BLEVE failure of a vessel was dependent on the amount of fuel in the vessel at the time of failure and the mode of failure.
- The resulting external radiation field, and hence received dosage, are dependent on these factors and also on the wind speed and direction as these effect the fireball trajectory during its formation.

• The duration of the fireball was seen to be, as expected, dependent on the mass of fuel in the vessel at the time of failure, varying from 3 seconds when 279 kg of propane was released, to 7 seconds when 1708 kg of propane was released.
• The maximum average surface emissive power measured during the experiments ranged from 270 to 333 kW m^{-2} up/down wind and 278 to 413 kW m^{-2} crosswind. The highest values were for the smallest release.
• The resultant fireballs gave their maximum power output before the fireballs reached their maximum volume and close to the lift off time.

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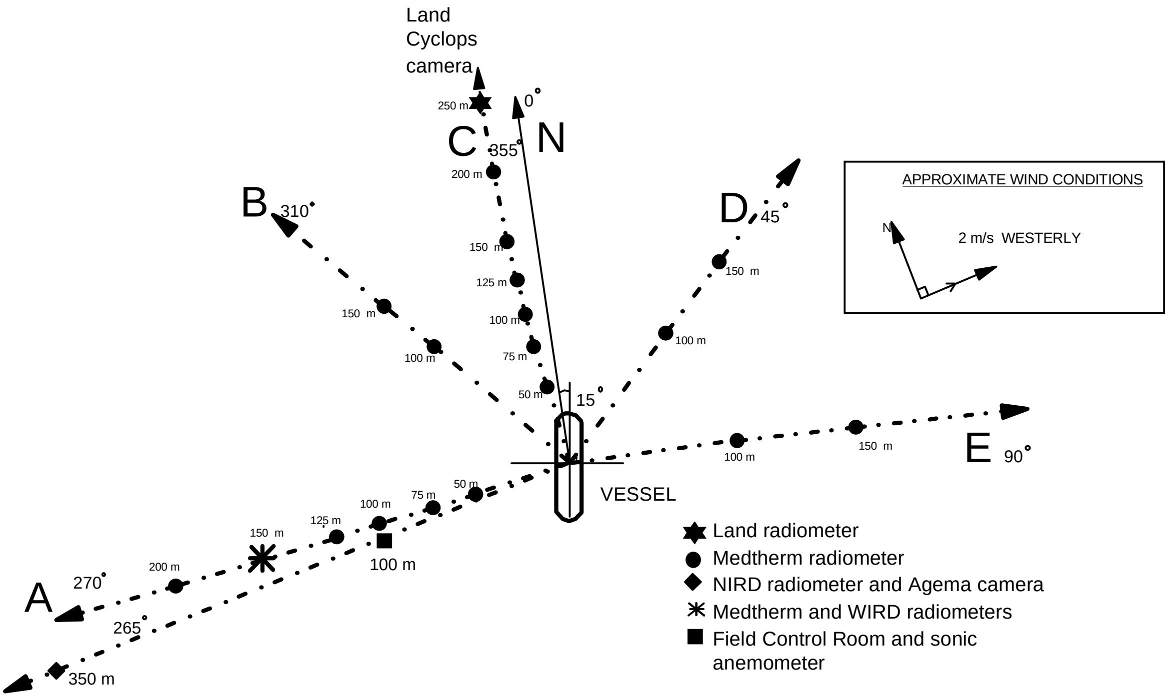


Figure 1. INSTRUMENT PLAN FOR 1708 KG RELEASE

279 kg

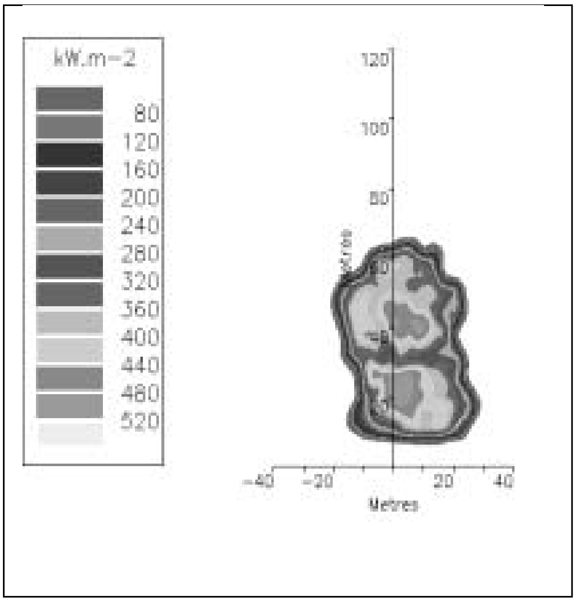
710 kg

1272 kg

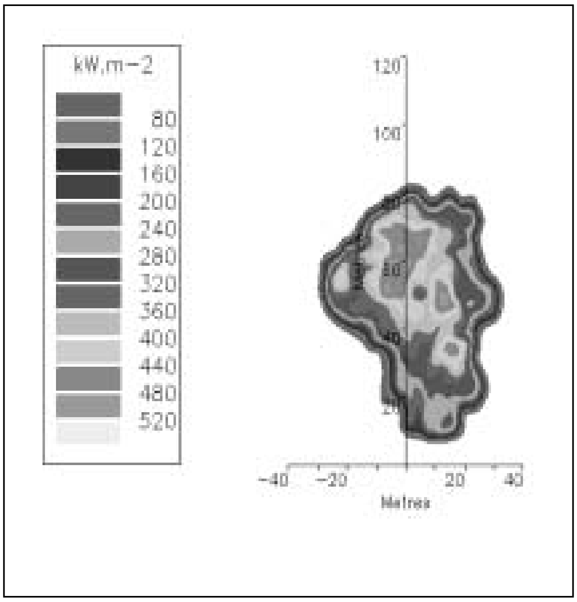
1708 kg

Figure 2. MAXIMUM SIZE FIREBALL FROM EACH TRIAL
(not to scale)

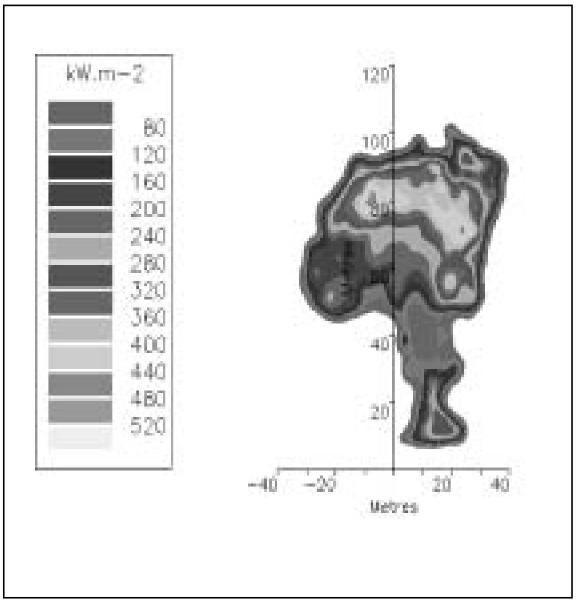
1.51 Seconds After Vessel Failure



2.60 Seconds After Vessel Failure



3.69 Seconds After Vessel Failure



4.83 Seconds After Vessel Failure

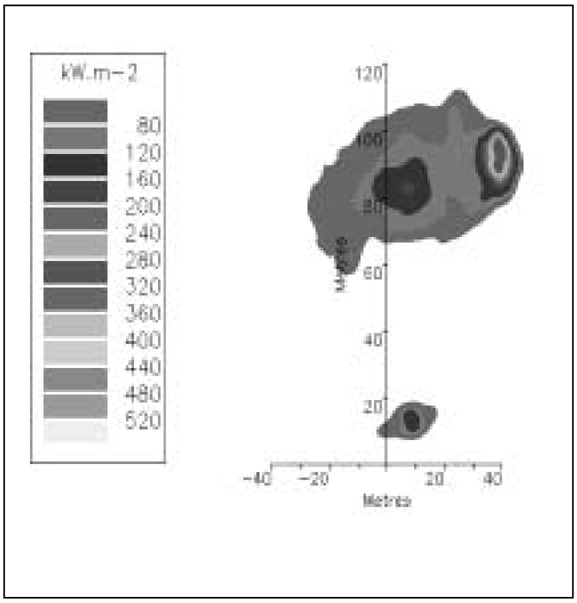


Figure 3. THERMAL IMAGES FOR 1708 KG FIREBALL GROWTH

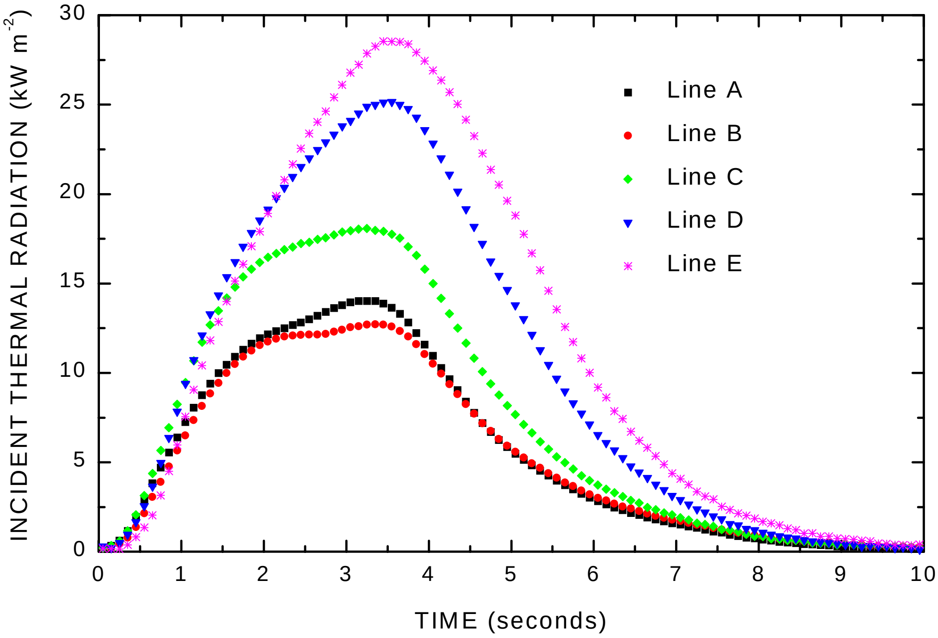


Figure 4. VARIATION OF IRRADIANCE AT 100 METRES (FOR 1708 KG RELEASE)

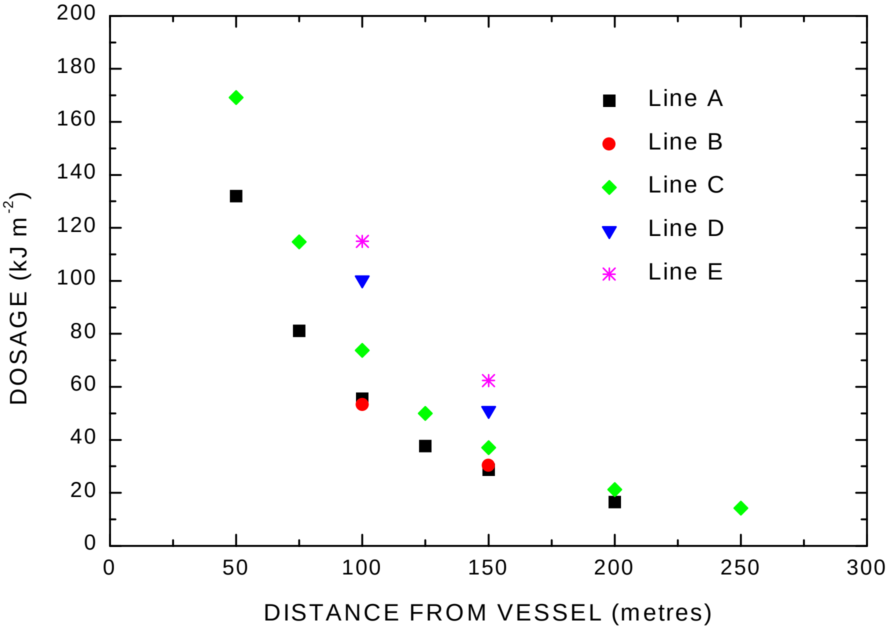


Figure 5. VARIATION OF DOSAGE AGAINST DISTANCE (FOR 1708 KG RELEASE)

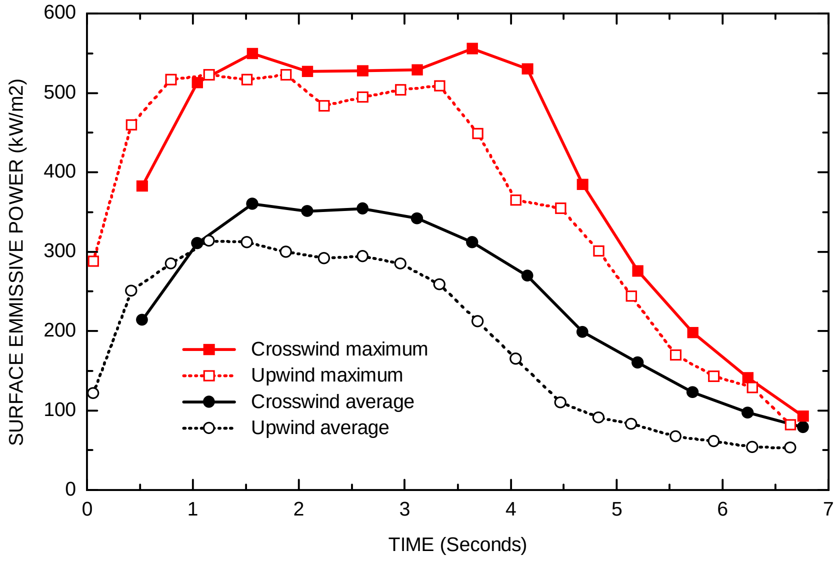


Figure 6. VARIATION OF SURFACE EMISSIVE POWER WITH TIME (FOR 1708 KG RELEASE)

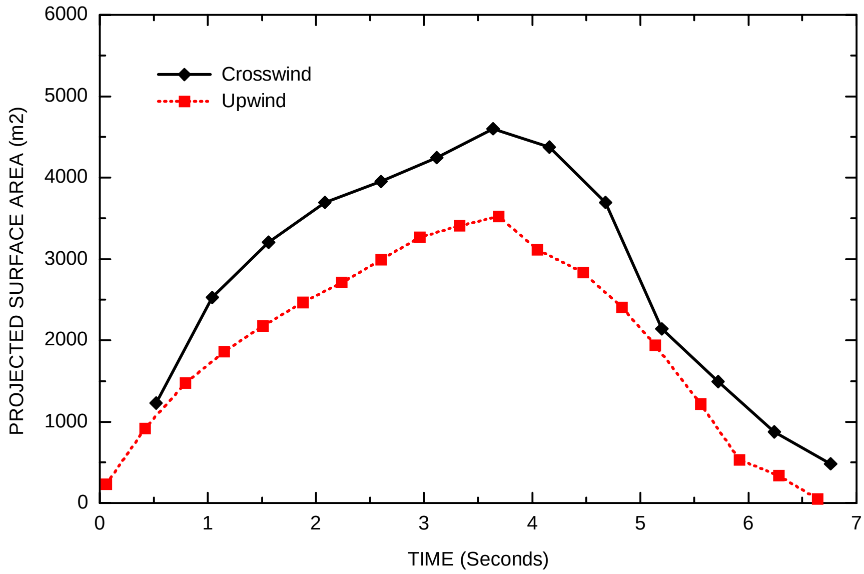


Figure 7. VARIATION OF PROJECTED AREA WITH TIME (FOR 1708 KG RELEASE)