AN EXPERIMENTAL STUDY OF LARGE-SCALE COMPARTMENT FIRES *

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A major experimental programme of large-scale compartment fires has been carried out by Shell Research at the Norwegian Fire Laboratory operated by SINTEF. Propane jet fires were burnt at 0.3kg/s inside a $135m^3$ insulated steel compartment with reduced ventilation to simulate accidental fires in offshore modules. These experiments have for the first time provided direct knowledge of fire development, heat fluxes, temperatures and toxic product concentrations for confined jet fires at realistic scale. Geometric effects (eg vent size, distribution) and jet source effects (eg orientation, momentum) on flame behaviour have been investigated. The results can be used to validate theoretical models of compartment jet fires - important for hazard identification, mitigation and protection on offshore platforms.

Keywords: Compartment fires, jet fires, offshore platform safety

INTRODUCTION

The behaviour of jet fires in ventilation controlled conditions has been little studied, and yet is an important scenario in hazard consequence analysis, particularly in offshore platforms, Cowley (1). Whilst the literature contains many accounts of under-ventilated cellulosic and pool fires, albeit at relatively small scale, the corresponding behaviour of jet fires remains largely unknown. The gas momentum of high pressure jets is expected to give rise to different phenomena such as enhanced mixing with air and recirculation of partial combustion products back into the flame. Thus, the effects on compartment wall and gas temperatures, heat flux within the flame and in the compartment volume, carbon monoxide levels, and external flaming are difficult to quantify. However, hazard analysts require such information to define the severity of the hazard and to design effective protection.

Consequently, a major experimental programme of large scale compartment fires has been carried out by Shell Research, Thornton at the Norwegian Fire Laboratory operated by SINTEF (part of the Norwegian Institute of Technology, Trondheim). We report here an overview of these unique experiments and novel findings on the global behaviour of compartment jet fires. Arrangements are being made with the U.K. Health and Safety Executive to publish the full data sets from these experiments in their Offshore Technology Series under Crown Copyright. Experiments involving pool fires and the effect of water deluge will be reported elsewhere.

BACKGROUND - THE NATURE OF COMPARTMENT FIRES

A hydrocarbon pool fire burning inside a compartment with a vertical opening produces hot combustion products which rise to the ceiling. If the opening is sufficiently large and the fire burns as it would in the open air, the fire size and intensity are controlled by the fuel burning rate. The flame from a pool burning under these conditions may impinge on the ceiling. The fire is deflected sideways and the plume spreads out into a so-called ceiling jet. This jet continues to burn until all the fuel is consumed, and may extend beyond the opening if the ceiling is relatively small and shorter than the ceiling jet flame extension.

If the opening is small, however, the fire may not be able to entrain enough air for complete burning of the fuel inside the compartment. The fire is said to be ventilation controlled. The air supply rate is controlled mainly by the geometry of the opening. In a short time, dependent on burning rate and vent size, a steady state is reached in which hot combustion products flow out of the top of the opening and ambient air flows in at the bottom. There normally exists a well defined boundary between the hot layer in the ceiling and the colder air at the floor.

This phenomenon forms the basis of zone models which have proved highly successful in describing the global quantitative behaviour of compartment fires (1). The most common assumption is that 3 zones exist each with uniform temperature. These are the fire plume itself, and the hot and cold layers. An important and robust result from zone modelling, Rocket (2), is that the maximum air flow rate into a compartment with vertical opening of area A and height H is given by the product $0.5A\sqrt{H}$ kg/s. Note, however that this result only holds if the thermal boundary is assumed to be at floor level, although there is experimental evidence to suggest that this is incorrect, and theoretical approaches can readily handle other zone locations.

The partial products from a ventilation controlled fire include carbon monoxide in concentrations which may pose a hazard at a downwind refuge. Under favourable conditions of composition and temperature, these products may become flammable. A flame may propagate into from the fire plume into the hot smoke layer and create flames external to the compartment. The sudden increased aeration and high temperatures in the external flame then reduce the CO concentration to levels more typical of open flames. Therefore, it is important to know the conditions which determine the onset of external burning and the extent of the new hazard posed by the external flame.

The behaviour of jet fires in compartments is expected to have some features in common with pool fires. For example, under-ventilation could lead to high CO levels, even exceeding those from pool fires because of the potential for generating higher temperatures in jet fires. External burning is also expected in some geometries. However, the validity of zone models is so far untested and one could argue that jet momentum effects could lead to a breakdown of zoning and the establishment of large recirculation vortices. Another difference between jet and pool fires is the absence of thermal feedback and "flashover" behaviour sometimes observed in compartment pool fires. The feedback results in a sudden increase in pool fire burning rate to a fully developed new steady burning regime.

The experiments reported here were designed to give direct insight into compartment jet fire behaviour and to test some of the expectations derived from theory, with the aim of providing a basis for the future development of computational hazard models.

EXPERIMENTAL PROCEDURE

A schematic of the 135m^3 compartment used in all the experiments is shown in Figure 1. The Figure also shows the general layout of the extensive instrumentation used in many of the tests. A photograph (no. 1) taken from the east wall looking west shows the general internal arrangement and instrumentation in the vent plane. The scale was dictated by the need to generate stable, optically thick flames and to allow sufficient residence times for the slower chemistry of the partial combustion products, whilst maintaining a reasonable practical size. The plate steel walls and roof were insulated with 150mm of Pyro-Log (Thermal Ceramics Ltd.). A cross section is shown in Figure 2.

All the jet fires were propane at a flow rate of nominally 0.3kg/s. Nozzle diameters of 17.8mm (sonic), 34mm (subsonic), and 4.5mm (liquid) were used to vary the initial jet momentum. Both vertical and horizontal nozzles were used. The vertical nozzle was placed in the centre of the compartment, and can be clearly seen in photograph 2. The horizontal sonic nozzle exit plane was located centrally, 1.025m in from the open east face. The jet was directed at a 0.27m diameter pipe target. The distance between sonic nozzle tip and middle radiometer in the target was 3.42m.

The target contained 4 total heat flux gauges (Thermogauge, model 1000-1), 2 ellipsoidal radiometers (Medtherm, model 64EP-10F-20544) and 12 thermocouples (Cromel/Alumel, Type K), arranged as shown in Figure 3.

Heat flux gauges and thermocouples were also present in the roof and west wall. In the first experiment (Test 1a, Table 1) a diagonal roof beam containing gauges, and visible in photographs 1 and 2, was not sufficiently insulated to avoid damage to the signal cables. The beam was removed for all subsequent experiments and spare gauges were secured directly in the roof panels, with the exposed face flush with the interior surface of the compartment. The wall mounted gauges were similarly attached inside a beam, at first. The signal cables survived intact during tests 1a, 1b, 2, and 3 but were destroyed by the intense heat generated in test 9b. All remaining tests therefore were performed with the wall gauges mounted directly in the wall panels themselves, similar to the roof mounted gauges, a set-up which by this time had proved successful. During each experiment, the gauges were held at a constant temperature of 55°C by flowing hot water through them. The ellipsoidal radiometers were continuously flushed with nitrogen at a flow rate of about 10l/min. All gauges were calibrated using a standard black body furnace set to a temperature of about 1100°C, at various stages throughout the test period.

Gas temperatures were measured using thermocouples (type K) on vertical strings. Three such strings were used throughout with the thermocouples roughly 0.5m apart. The first (east string) was located halfway between the vertical opening and centre of the compartment. The second (west string) was halfway between centre and back wall. The third (south string) was in the same plane as the west string but halfway between longitudinal centre line and south wall.

The ventilation opening was varied from fully open to 2.5x2m open as shown in Figure 1, using a 2mm thick steel sheet for blanking. Vent pressures were measured by bi-directional pressure probes linked to pressure transmitters. The probes were located on the vertical centre line, to measure pressure variations in the outgoing products and incoming air, and on the vent diagonal, to record possible non-uniformities across the vent plane. Vent temperatures were measured using type K thermocouples close to the bi-directional probes and additionally between probes along the vertical centre line. Vent velocities were then calculated by the method developed by McCaffrey and Heskestad (3).

Combustion product (CO, CO_2, and O_2) concentrations at the vent plane were monitored by continuously drawing samples for analysis from the upper portion of the gas stream emerging from the vent. Sample locations were chosen at three positions and the streams combined in an attempt to obtain representative gas concentrations in the emerging products. Soot levels were measured by a light extinction apparatus in a duct designed to divert some of the emerging smoke. This duct and the gas sampling probes are shown in Figure 1, and are clearly visible in photograph 1.

External flame radiation was measured by two radiometers (Medtherm, wide angle) one of which was located in the vent plane about 10m to the north, and the other viewed the vented wall directly. Both radiometers were oriented to receive maximum radiation. Clearly, the latter radiometer would receive radiation from the interior of the compartment and the hot steel plate covering part of the vented wall, as well as that from the external flame, and the results are not reported here.

Extensive use was made of video and still photography. These were invaluable for recording flame development inside and external to the compartment. Three video cameras were arranged to view the interior of the compartment, two of which viewed the flame in close-up through small heat resistant glass windows. The third camera was located in an easterly direction to record flame development as seen through the vent. A fourth camera was located in the vent plane near the north radiometer to record the size and position of the external flame. The video timers were sychronised with the data stream from all the other instruments.

Data were sampled every 2 seconds and logged by means of the data acquisition system developed by SINTEF and stored as a file on computer. After data processing, the application of calibration constants and calculations could be readily performed using Lotus Symphony and Lotus 123 spreadsheet programs.

RESULTS AND DISCUSSION

It is convenient to report and discuss the results for each individual experiment and then make comparisons between experiments at appropriate stages. Summaries of the more important and interesting data can be found in Tables 2 to 5 and Figures 4 and 5.

Experiment 1a - Sonic gas, vertical nozzle, wall fully open.

A lifted conical flame, typical of open flames, but impinging on the ceiling persisted throughout the experiment. The vent flow data at steady state in Figure 4 indicate that the flame is well aerated and hence burning under fuel controlled conditions. The average inflow velocities and temperatures in the lower half of the vent suggest a mass influx of air of about 12kg/s. This is about three times the stoichiometric requirement of 15.6 times the fuel mass flow rate, or 4.2kg/s. Thus the behaviour and air entrainment of the flame is similar to that of an open flame.

The visible flame length L_o would normally have been about 8m in the open, Chamberlain (4), but deflection by the ceiling and walls set up the vortical flows evident in plate 2. The ceiling flame extension R was 2-3m which is consistent with a simplified form of a correlation, You and Faith (5), derived from pool fire data,

$$R = 0.5\ (L_o - h).$$

In this equation h is the height of the ceiling above the nozzle tip. In the experiment $h = 3.4$m i.e. nearly halfway up the flame axis. At this distance the flame is becoming buoyancy dominated. The above equation was derived for purely buoyant flames and the present result suggests that it is generally applicable. We do not however expect that the correlation holds for flames that are momentum dominated at the impingement point, but this aspect was not tested.

Steady ceiling temperatures of 1150°C were reached after nearly 4 minutes. The initial heat flux in the impingement area was 200-250 kW/m^2 rising to 300 kW/m^2 as the radiative contribution from the hot walls increased. An interesting effect was observed at the two total heat flux gauges in equivalent radial jet positions. These gauges were both located 0.955m from the point in the roof directly above jet centre line, see Figure 5. One gauge was in the beam support 0.15m lower than the ceiling, whereas the other (the reference gauge) was in the ceiling plane. For comparison purposes, this small difference in heights is regarded as insignificant. The heat flux at steady state at the beam gauge was 170kW/m^2 while that at the reference gauge was 300kW/m^2. This considerable difference in received heat flux is thought to be caused by a significant drop in the convective heat flux component of the total heat flux on the beam gauge. Significantly, a beam gauge located on the jet axis received a heat flux loading similar to that of the reference gauge.

There was very little smoke produced in this test and CO levels were less than 0.1%v, consistent with values expected of a fuel controlled sonic propane flame.

Experiment 1b - Sonic gas, vertical nozzle, wall partially open.

In this experiment the vent area was reduced to 2x2.5m (height x width) as shown in Figure 1 and photograph 2. The roof beam was removed after the damage caused by the first test and the gauges were secured directly in roof panels (see Experimental section). An average propane gas flow of only 0.21kg/s was achieved in this test, somewhat below the target value of 0.3kg/s.

Flame development in the early stages was similar to 1a. A conical lifted flame impinged on the ceiling and produced recirculation eddies at the walls. Thereafter, flame behaviour became quite different. When the air inside the compartment had been consumed by the flame, a two-way flow of outgoing combustion products and incoming fresh air established itself at the vent. From about 50 to 100 seconds after ignition, the flame became blue in colour, characteristic of pre-mixed propane and a blue flame emerged from the top half of the vent. The conical jet flame lifted further and lost its well defined shape. At this stage the vent velocity and temperature measurements suggest that the flame was becoming ventilation controlled, i.e. there was just enough air to meet the stoichiometric flame requirement. The propane jet and compartment began to act solely as a source of turbulent fuel gas, and flames filled all but a narrow layer near the floor. After this stage the flame became increasingly sooty both inside the compartment and in the external flame. The gas temperature in the upper layer rose uniformly to 700-900°C during this phase, sufficient to pyrolyse any unburnt propane. The hot soot formed in this process increased the radiative contribution of total heat flux after an initial drop during the blue flame period.

Final gas temperatures of 1150°C were reached concommitant with maximum heat fluxes of over $300kW/m^2$ in the ceiling. Photograph 3 was taken during these final stages. Measurements taken in the vent suggest a mass inflow rate of air of about 3kg/s (average air velocity 3m/s, average temperature 450°C, height of thermal discontinuity 0.9m from Table 5. Note that the value of $0.5A\sqrt{H}$ is 3.5kg/s air in all the partially ventilated experiments). The average propane flow rate of 0.21kg/s requires 3.3kg/s of air for stoichiometric burning, so the flame is only slightly under-ventilated. This would account for the small quantity of smoke production and the rather limited size of the external flame. On the other hand, the fire loading inside the compartment is severe in terms of heat flux and temperature rise and possibly represents a worst case for this combination of vent size and fuel flow.

Experiment 2 - Subsonic gas, vertical nozzle, wall partially open.

The overall behaviour of the subsonic flame was again quite different, especially in the early stages. A dark smoke layer built up in the roof space over the first 90 seconds from ignition of the fuel jet. Some smoke issued from the vent, but no flame, during this time. At 94s fingers of flame emanating from the main jet flame started to appear on the underside of the smoke layer. The flame fingers gradually spread out to engulf the whole of the underside of the smoke layer, until at 98s, a fireball emerged from the compartment.

The maximum CO concentration in the smoke just before flame emergence was 4-5%v at temperatures ranging from 150°C at the bottom of the smoke layer to 500-600°C at the top. Note however that the temperatures at the vent were rising rapidly (about 40°C/s) in the period from ignition of the smoke layer to appearance of the fireball.

These phenomena displayed by subsonic flames were quite reproducible irrespective of jet orientation (see expt.8). The CO concentration in smoke is an important hazard to consider in quantifying the threat to personnel caught in the smoke plume. The values measured here could be used as the vent source terms in subsequent smoke plume dispersion calculations.

Ignition of the smoke layer and external flaming oxidise the CO to CO_2 thereby reducing the CO concentration at the flame tip to levels typical of open burning flames, although direct measurements of CO levels would be useful in confirming this supposition. The CO concentration within the flame can still be high however, and 5-6%v was measured within the external flame in many of the ventilation controlled experiments. It seems reasonable to suppose that the main threat to personnel from CO then arises if the refuge is engulfed by flame rather than by smoke.

Vent measurements confirm that the fire was ventilation controlled. The air mass influx was about 2.2kg/s compared with a stoichiometric requirement of 3.9kg/s, giving an equivalence ratio of 1.8.

The uniformity of temperature in the upper layer at steady state was remarkable (see Table 2), and zone modelling may yet prove to be a useful tool in simple modelling of the global behaviour of compartment jet fires.

Experiment 3 - liquid propane, vertical nozzle, wall partially open.

This experiment produced copious amounts of smoke throughout and heat fluxes were in general lower than in the previous tests. An external flame was always present during the ventilation controlled phase. Vent measurements indicate that the air mass influx was about 2.5kg/s at steady state, giving an equivalence ratio of 1.9. The external flame was considerably larger than in previous experiments indicating less efficient combustion inside the compartment. This can be explained in part by a reduction in air entrained by the lower momentum liquid jet and in part by the slightly higher fuel mass flow rate.

Experiment 9c - sonic gas, horizontal nozzle, wall fully open.

This experiment was similar to 1a except that the nozzle was horizontal and the jet was directed towards an instrumented pipe target located across the centre of the compartment. As expected, the flame behaved as if in the open. The end of the flame just reached the far wall and combustion was always in the fuel controlled regime. There was very little smoke and only a trace amount of CO.

Experiments 9a and 9b - sonic gas, horizontal nozzle, wall partially open.

In these experiments the opening at the east wall was reduced to the same as that in the equivalent experiment 1b using the vertical nozzle. Initially flame behaviour resembled that in 1b and a blue flame developed. Interestingly, the lifted flame did not anchor itself to the target in experiment 9a but lifted away completely to the far end of the compartment. The results and observations suggest that the target played little part in determining flame development and behaviour, and any differences between the two sets of results, 9a and 9b, can be explained in terms of the differences in fuel mass flow rate. Combustion in experiment 9b was closer to stoichiometric (equivalence ratio 1.6, compared with 2.1 in 9a) and hence higher temperatures and heat fluxes were generated as well as less smoke and a smaller external flame.

A notable feature of these experiments was the fact that higher heat fluxes were recorded near the bottom of the upper hot layer. Presumably air entrainment into the horizontal jet is favoured by the proximity of the jet to the lower air layer. Photograph 4 shows the appearance of the flame at steady state.

Experiment 8 - subsonic gas, horizontal nozzle, wall partially open.

Flame behaviour in this experiment was similar to that in experiment 2 in that an unignited smoke layer built up in the upper layer of the compartment in the early stages. The maximum CO concentration at this stage was however somewhat lower at 2.5%v.

This experiment produced the greatest amount of smoke and highest soot concentrations, see Table 4. Analysis of the vent flow suggest that the equivalence ratio was about 2.9, also the highest value derived in this test series.

Experiment 6 - sonic gas, horizontal nozzle, roof partially open

The roof was opened up to the same extent as in the previous ventilation controlled experiments. Initially a blue flame developed inside and outside the compartment, as before, but after only 75s from ignition the flame extinguished due to lack of oxygen. Before extinction, rapid oscillations were observed in the external blue flame. It appears that the establishment of a two-way equilibrium flow of air and combustion products is not favoured by this geometry, and the flame becomes highly unstable.

CONCLUSIONS

A series of compartment jet fires at large scale have been carried out to study the general phenomenology using propane as the representative hydrocarbon fuel. The geometry of the compartment and jet characteristics have been systematically varied to obtain new insight into compartment fire dynamics. The overall behaviour and fire development are complex and will be discussed elsewhere, but some general conclusions can be drawn:

1. In these experiments, the time to steady state for ventilation controlled jet fires with vertical openings is about 10 mins.

2. Flame stoichiometry is controlled by the size of the vent opening, fuel flow rate and jet momentum.

3. Flame stoichiometry is an important parameter which governs soot and smoke production, CO concentration, and size of the external flame. Fuel rich flames produce increasingly more smoke and CO, and have larger external flames as the equivalence ratio increases. The parameter $0.5A\sqrt{H}$ determines a maximum air inflow rate thereby over-estimating air entrainment, and is not recommended for calculation of flame stoichiometry.

4. Gas temperature in the upper layer is remarkedly uniform at steady state, and can reach about 1200°C, suggesting that zone modelling may be justified to some extent.

5. Gas temperatures and heat flux values are intimately associated with soot production, ventilation controlled heat release rates and heat loss through the compartment boundaries. A jet fire burning under slightly fuel rich conditions combines high heat release rates with enhanced soot production, and generates high compartment temperatures and large radiative heat flux.

6. The neutral plane defining the boundary between outflowing products and inflowing air, is normally about halfway up the vent, reducing in height slightly with increasing equivalence ratio.

7. Roof ventilated jet fires are unstable when ventilation controlled and self-extinguish.

The results may be useful to combustion theoreticians, modellers and safety engineers involved in the identification and mitigation of fire hazards.

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Table 1. **Summary of compartment jet fire tests**

Test No.	Propane state	Average flow rate, kg/s	Orient^n of jet	Height of nozzle m	Vent size m (height x width)	Vent location	Target in place?
1a	gas/sonic	0.27	vertl	0.52	4 x 3.5	end wall	no
1b	gas/sonic	0.21	vertl	0.52	2 x 2.5	end wall	no
2	gas/subsonic	0.25	vertl	0.38	2 x 2.5	end wall	no
3	liquid	0.30	vertl	0.39	2 x 2.5	end wall	no
9c	gas/sonic	0.24	horiz	1.01	4 x 3.5	end wall	yes
9a	gas/sonic	0.30	horiz	1.01	2 x 2.5	end wall	yes
9b	gas/sonic	0.24	horiz	1.01	2 x 2.5	end wall	no
8	gas/subsonic	0.30	horiz	1.01	2 x 2.5	end wall	yes
6	gas/sonic	0.24	horiz	1.00	2 long x 2.5 wide	roof	yes

Table 2. **Summary of temperature data.**

Test No.	Time to steady state,s	Maximum gas volume temps, °C						Max. wall temps, °C		Max. roof temps, °C	
		East		West		South					
		top	bottom	top	bottom	top	bottom	top	bottom	centre	edge
1a	200	1100	500	1100	650	1100	450	900	600	1150	950
1b	400	1120	1080	1150	1050	1150	1050	1020	820	1120	1030
2	600	1200	1200	1160	1100	1050	1150	970	920	1200	1100
3	500	1220	1220	1080	950	1130	900	900	850	1200	1030
9c	200	800	800	950 (1180 mid)	850	1000	600	950	700	810	610
9a	500	1100	1050	1100	1050	1100	1050	1050	1050	1040	990
9b	500	1180	1180	1240	1240	1250	1250	>1350	1300	1200	1100
8	600	-	-	1140	1140	1150	1150	1160	1100	1100	1050
6	flame out at 75s	670 (maxima: (700	410 710	480 800	490 710	500 670	510 670)	420	280	380	240

Table 3. **Summary of target measurements.**

Test no.	Maximum heat flux, kW/m^2						Maximum temperatures, °C				
	Radiometers Middle		Total flux Middle		End		Middle		End		Max and location
	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	
9c	60	90	230	170	220	240	720	760	720	750	860 end/top
9a	85	40	170	120	190	170	600	600	720	740	880 end/top
8	70	20	100	60	120	135	625	665	775	805	967 end/top
6	no data	80 (20	190 70	no data	145 50	145 50)	160	130	120	110	172 mid/top
		(values at flame extinction)									

Table 4. **Summary of vented gas and soot measurements.**

Test No.	Gas concs, %v dry gas at steady state oxygen	carbon dioxide	carbon monoxide	Description of smoke	Soot conc. g/m^3
1a	14.5	4.3	0.03	trace amount	0.02
1b	no data	10.5	2.5	small amount	0.03
2	0.6	8.5	>2.5	some in early and late stages	0.3
repeat test	0.5	10.0	4.0 (4-5% in smoke just before external flame)		0.2 before external flame
3	1.0	8.0	6.0	copious amount	1.5
9c	12-13	5.5-6	<0.01	trace amount	0.005
9a	1.0	8.0	5.5	large amount	1.5
9b	1.0	9.0	5.0	small amount	0.1
8	1-1.5	7.0	6.0	copious amount	2.0
6	9.5-14.5	6.5-3	1-1.5	trace amount	0.004 at flame extinction

Table 5. **Summary of external flame measurements.**

Test No.	Max. flame extent at steady state, m		Height of flame bottom edge above floor at steady state, m	Side-on radiation at steady state, kW/m^2
	Vertical	Horiztl		
1a	0	0	n/a	-
1b	3	2	0.9	0.9
2	4	2.5	1	1.0
3	6	3	0.8-1	1.0
9c	0	0	n/a	-
9a	5	3	0.8-1	1.7
9b	4	2.5	1	1.3
8	5	3	0.5-1	1.8
6	3	2	n/a	no data

Co-ordinates of side-on radiometer, m (x,y,z) -0.62, -10.5, 3.65. Origin at base of east wall, in north-east corner.

Figure 1

Schematic of Fire Compartment and Instrumentation

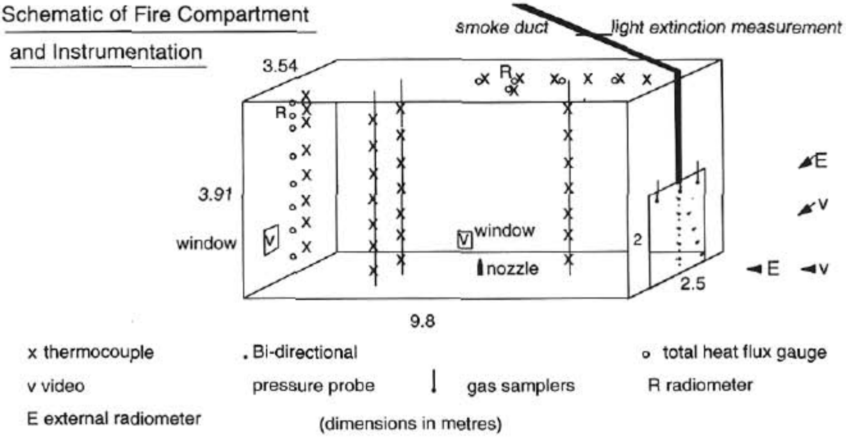


Figure 2

Cross Section of Insulated Wall Panel

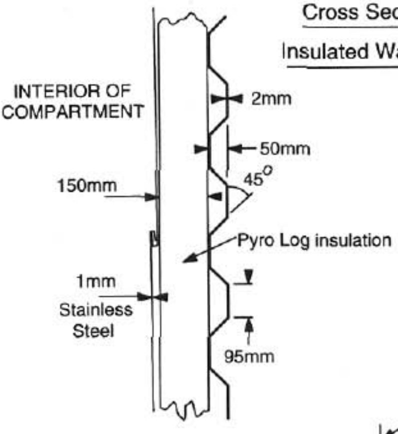
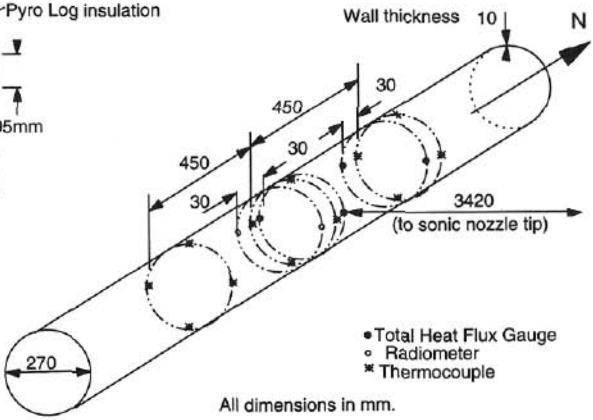


Figure 3

View of target showing instrument positions



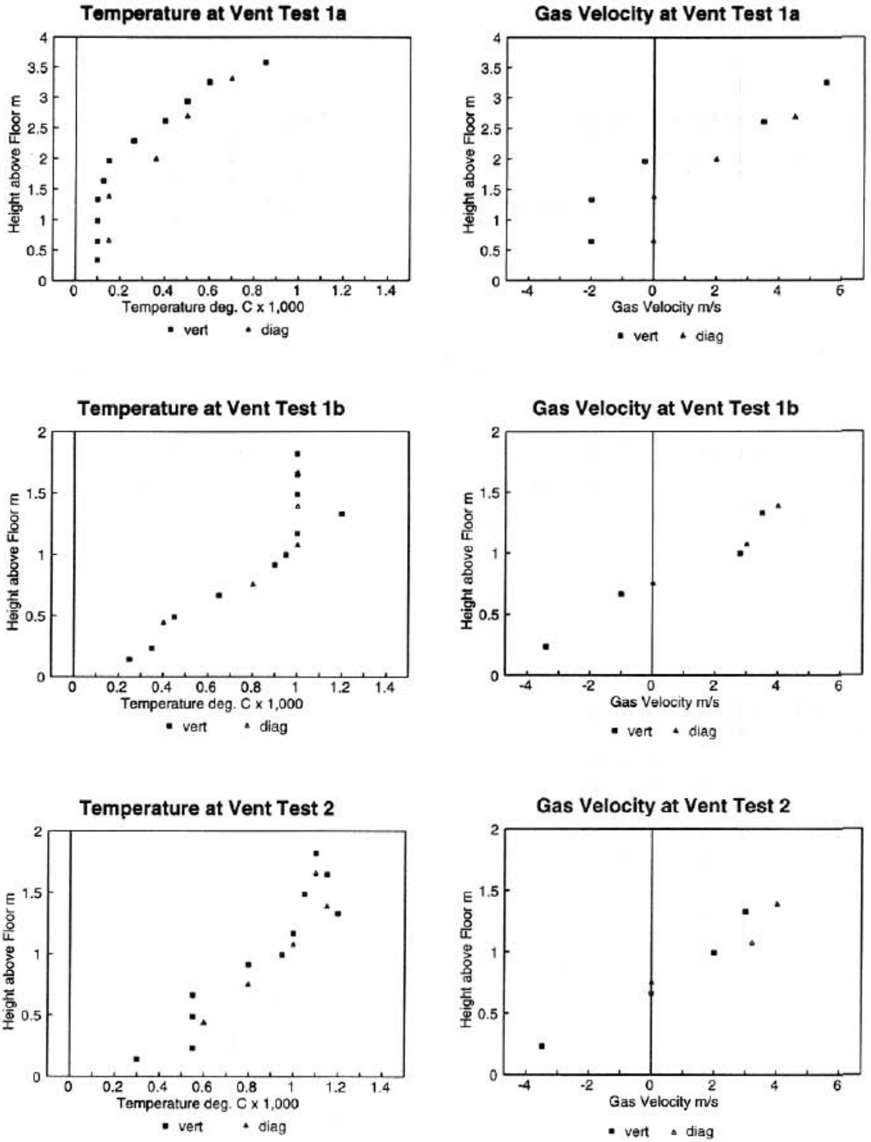
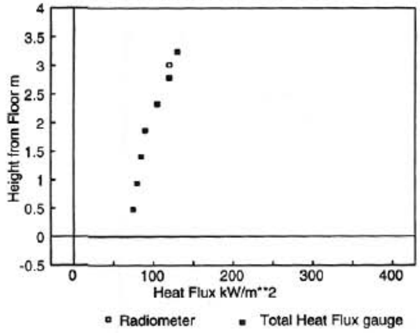


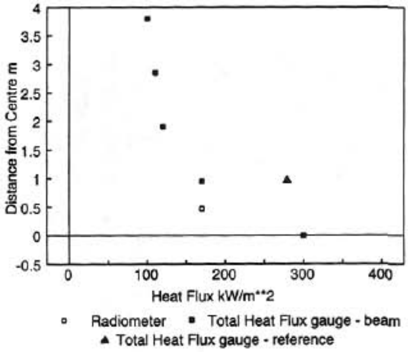
Figure 4

Variation of temperatures and gas velocities with vent height for tests 1a, 1b and 2

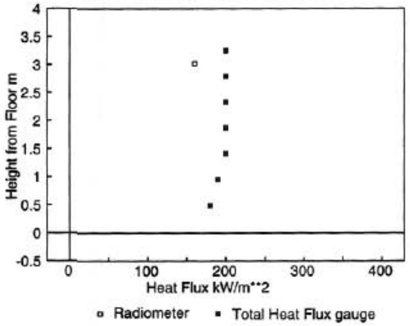
Heat Flux at Rear Wall test 1a



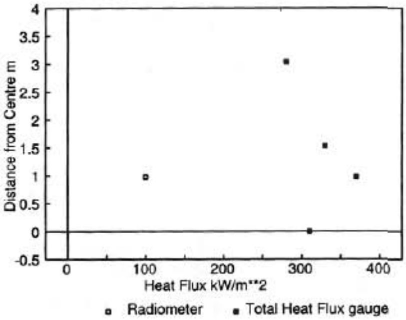
Heat Flux at Roof Test 1a



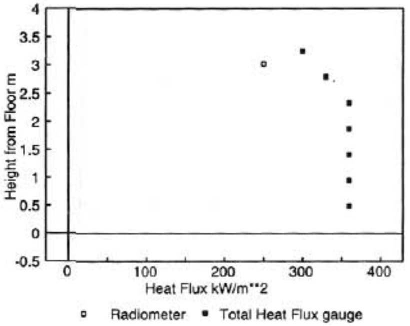
Heat Flux at Rear Wall Test 1b



Heat Flux at Roof Test 1b



Heat Flux at Rear Wall Test 9b



Heat Flux at Roof Test 9b

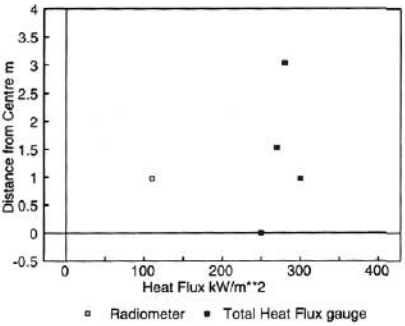
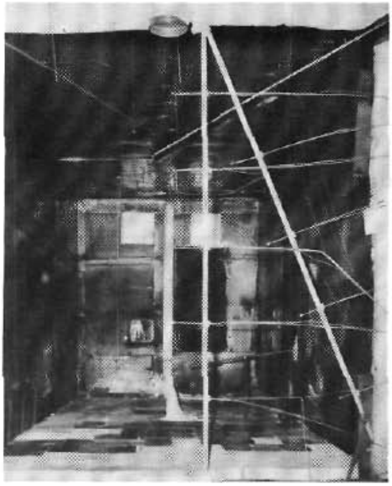
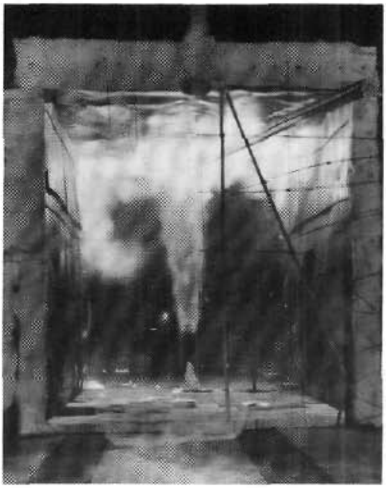


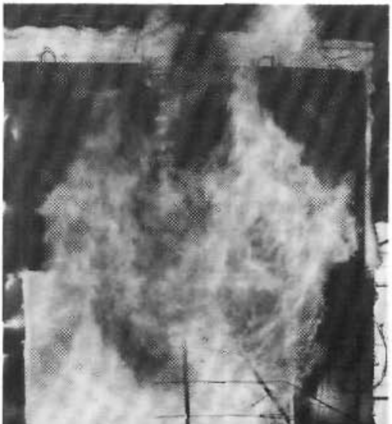
Figure 5
Variation of incident heat flux at the wall
and roof in tests 1a, 1b and 9b



1.



2.



3.

4.

Photographs of the test compartment from the East(1)
and flames at steady state in experiments
1a (2), 1b (3) and 9b(4)