Some Comments on Fire Spread in High Racked Storage of Goods

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Summary

A number of reports have been examined of tests undertaken by FRS and by FIRTO for the purpose of studying the behaviour of sprinkler systems in controlling fires in piles of stacked cardboard cartons. Mean speeds of the rising flame tip have been estimated and found to be very variable. Typically if ignition is on the vertical outside "face" speeds are 1-3 cm/sec. Ignition in a "flue" is typically 10 cm/sec. Although these are data for different transverse and vertical gaps these factors were not studied systematically and no associations have been found with the variable mean speed data. In one study the transverse gap was changed but so was the ignition system. There is consistant evidence of an increasing tendency for fire to spread sideways into horizontal gaps as it ascends.

1 Introduction

The problem of extinguishing a fire in a pile of goods, or if not extinguishing it, of controlling it (the purpose of a sprinkler system is not always stated unambiguously) has been investigated for several decades.

Much of the early work was done by insurance based organisations (e.g. in the U.K. the Fire Offices' Committee or the Loss Prevention Committee) and some reports are not in the public domain. Likewise some more recent work has been done to protect military establishments and that too is subject to restrictions. Summaries are sometimes available and one of these is extensively used in this report, with other reports in the public domain. These are mainly concerned with improving the detection and sprinkler systems and although there are records of the fire growth prior to the operation of a sprinkler it must be remembered that the effect of various factors on fire growth was not the area of any investigation so far reported in the UK.

In no cases prior to 1992 are there any UK data on the rate of heat release - or of mass loss. There are visual records of the position of the rising flame and many video records but the camera was not necessarily set at a level or in a line of sight to get precise data on flame spread.

Often thermocouples were installed in the gaps between packed goods. A few measurements of smoke visibility AND radiation were made but no use has been made of them here, partly because the coverage was rather low.

2 Sources of Data

The literature examined in this report is comprised of UK data obtained from the Fire Research Station, Borehamwood and from the Loss Prevention Council, Borehamwood. Other data from the Factory Mutual Cooperation, USA, are reported elsewhere.

2.1 Early Experiments [1],[2],[3] and [4] (1970-1972)

The loading was 32 standard wooden pallets 1.02 m x 1.22 m each loaded with cardboard cartons. Each carton contained three empty 5 gallon drums with some wood wool in the spaces between them - each layer being 1.37 m high; the whole stack being 5.68 m high (4 levels). Spaces between the vertical flammable surfaces were usually 75 mm - some were 150 mm.

Thermocouples were placed in the gaps near the outside face of the stack and near a sprinkler. Radiometers were placed around the stack and some measurements made of the observation of smoke. Various experiments were made with ignition in the centre gap or on the face (one carton was torn open to provide easily ignited fuel by exposing the wood wool).

Chronologies and some temperature time data are reported. From the chronologies one can estimate the rate of vertical rise of the flame tip (see figs (1) and (2), taken from references 2 and 3, respectively). Conclusions concerning fire growth prior to the opening of a sprinkler were that:

1. Fire could spread up the faces of the various layers if the vertical gaps were small enough (1/3 of the total height of a single layer); otherwise fire spread into the centre of the stack: there was a tendency for sideways spread along horizontal gaps.
2. From Reference 3 (FR 914), which reports many tests with a similar ignition procedure and fuel arrangement, one can obtain the times for flames to reach the top of each of other layers of boxes. In one test the fire had to be restarted and Table 1 gives the intervals in seconds from the restart.

Table 1 Ignition at centre of front face. Times from bottom to top of each layer in seconds.

Test	S 2/1	/2	/3	/4	/5	/6	/7	/8	/9	/10
Top of 1st Box	40	30	10	35	30			25		65
Top of 2nd Box	35*	190	115	100	230	95	70	185	90	95
Top of 3rd Box	65*	-	45	40	55	25	45	35	55	35

* Preheated because of the restarting of the fire

Table 2 (mean values from Table 1)

Test	Mean Values	Total-sec
1st Box	33	33
2nd Box	113	146
3rd Box	42	188

The 146 secs for the 1st 2 layers was the mean of 10 data varying from 70 to 260 secs.

The first interval varied from 10 to 65 s.

The initial growth of the flame appears to be dominated by the ignition source, with only a weak contribution from the spread. The third stage proceeds nearly three times faster than the second. Nevertheless there is nearly ± 100 % variation in speed. A few earlier experiments [1], [2] exhibited the same variation. The authors say:

"The initial rate of growth of flame height was low, due to the need for the fire to propagate from a small source. After the initial growth, the fire accelerated rapidly, taking about the same time to grow from 1.5 to 9.0 m (5 to 30 ft) flame height as it had taken to grow from 0 to 1.5 m (0 to 5 ft). The short times involved meant that any effect of cardboard moisture content was relatively unimportant in the second stage."

These higher speeds correspond to about $\approx$ 3 cm/s. There was less emphasis on recording flame height in reference [4], but such data as are recorded are comparable with the above.

2.2 The "Fire Surveyor" paper, [5].

In a paper some 10 years later, after a major fire in an HMG Ministry of Defence warehouse Peter Field summarized previous work by the Fire Research Station up to the mid 80's. The emphasis was on the performance of sprinklers and their systems. The ignition position was varied, on "face", as above, and in a "flue" but some changes had been made in the width of the "flue" channels.

Fires ignited within the flue spread rapidly upwards (a <u>mean</u> speed of 4.5 cm/s). "The flame propagation was rapid enough to involve boxes on the upper levels before the box contents (wood wool and polystyrene clips) became involved; lateral flame spread at this stage was minimal."

"Fires ignited on the face of boxes led after, say, 7 min to flames moving towards the centre of the stack and behaving as if ignited in a flue".

An increase in box spacing from 75 to 150 mm i.e. the dimensions of transverse and longtitudinal flue, resulted (for flue ignition) in an increase in the speed of spread.

Unfortunately the reported dimensions of the increased spacing and the changes of velocity do not seem to permit any quantitative analysis. The change in the spacing from 75 mm to 150 mm was, it seems, accompanied by a more powerful ignition procedure (c.f. Table 3 and 4 of that report). The effect of doubling the spacing appear to be a decrease in the mean time of spread from about 8 min 4 sec to 6 min 20 sec an increase of speed by a factor of 520/380 i.e. c:a 35 %. The heat transfer for given radiation levels depends only on the distance in relation to the size of the source. Doubling the spacing, to a first approximation doubles the size of the advancing source of radiation. Its effect extends forward twice the distance but the ignition time is unchanged. We would expect therefore a doubling of the speed rate for a radiation driven spread and perhaps more if flame emissivity increases on larger scale. We conclude that the system is not wholly radiative.

Many experiments were conducted with ignition on the "face". This led to spread into a flue and the time at which this was recorded was taken - in the reporting - as ignition in the flue allowing the same experiment to give data for "face" and "flue" ignition.

The conclusions of this report relating to fire growth refer only to fires spreading up the height of the rack 10 m of rack within 2 min - a <u>mean</u> spread of 8 cm/sec.

2.3 Data taken from an unpublished report

In the mid eighties interest in high rack fires was reawakened at FRS by the Donnington (Ministry of Defence) fire, but again the <u>main</u> emphasis was on the arrangement of sprinklers and other design.

Tests were performed on an assembly of six levels of four pallets, each containing two cardboard boxes. There existed therefore two flues between boxes - at right angles to each other in which thermocouples were placed. No other instrumented record was made. Remarks such as "difficult to obtain precisely the same results from repeated tests, due (sic) to the number of uncontrolled variables" and "broadly similar results" permit some general comments and draw attention to the variability and the difficulty of ensuring repeatability. No suggestion is made as to the source of the variability but obviously there is a difficulty, perhaps an impossibility, of ensuring constant moisture levels in large fuel beds in a large laboratory. It clearly is doubtful if a gap nominally 75 mm is uniform throughout a stack and ignition and early spread resulting from exposing some undefined amount of wood wool from a torn carton will be variable.

Reference is made to exponential fire growth (Alpert and Ward, Fire Safety Journal, <u>7</u>, 127, 1984) but no confirmation nor comparison is made for these experiments. The data show spread up of the flue (from the "face ignition") reached the 6 th level (5x1.83 m) 90 secs after ignition within the flue, 344 sec after the <u>initial</u> ignition. This gives a <u>mean</u>

speed up the flue of

$$\frac{5 \times 1.83 \times 100}{90} \approx 10\ cm/\text{sec}$$

This is as high as is recorded in any data and is roughly 3-5 times faster than on the face. This is despite the lesser availability of oxygen. The procedure of discussing "flue" ignition from a time zero when flames have spread into the "flue" from a "face" ignition has been fairly general. Data resulting from it neglects completely any contribution of preheating and unfortunately little or no data have been found not subject to such limitations.

Some data were obtained with a spacing of 100 mm (see below).

3 Problems of gap size

Comparisons between the behaviour with different gap sizes appear, it seems, only in the one open reference [5] but the ignition source was changed or only one test was made at the large spacing.

A direct comparison between the times from level 2 to level 3 is given below

Table 3 The rise of flame tips (flue)

FRS Test Code	Time to reach level 3 less time to reach level 2	Spacing
FR16	13 sec	75 mm
FR18	17 sec	75 mm
FR24	11 sec	150 mm

Ignition of the outside faces ought not be different but, for spread from level 2 to level 3 they are as given in table 4.

Table 4 Rise of flame tips (flue)

	Time interval-sec	
FR16	25	75
FR18	35	75
FR24	14	150

These differences are presumably the result of the "enhanced" ignition.

In the unpublished report referred to above some data for 100 mm gaps are given. Here ignition was effected simultaneously in two places, one "face" and one "flue", so the data are again not comparable. The time to spread in the flue from level 2 to level 3 was in three tests 25 secs, 12 secs, 19 secs, a mean of 19 secs; longer than for the 75 and 150 mm tests but possibly reflecting experimental differences in ignition etc.

4 Discussion of above

It is to be expected that spread speed increases with gap size for very small gaps (air limitation) and self extinguishing on each face of a very wide gap when the sides are independent. This suggests there is a gap size with a highest spread rate but clearly three dimensional features of the flow are involved too.

1. Differences in experimental conditions, particularly in the ignition, make the early development prior to the opening of sprinklers too variable for comparison to be reliable.

2. In the flue mean spread rate can reach 10 cm/sc or more whilst spread up the "face" is of order 1-3 cm/sec.

5 The acceleration of flame spread

Data are available only for the position of flame height "L". Data on the size of the pyrolyzing zone are not available.

In a first approximation the rate of heat release $\dot{Q} \sim L^{5/2}$ for a three-dimensional flames.

Hence the rate of increase in $\dot{Q}$ increases with time for any increase in flame height, L, faster than $t^{2/5}$.

For line ignition the 2/5 is replaced by 2/3. Fig(1) and (2) show how L(or $\dot{Q}$) vary with time; generally increasing except perhaps initially. Doubling times for L are of order 1/2 - 1 min so that doubling times for $\dot{Q}$ are of order 12 - 25 sec (three-dimensional) or 20 - 40 sec for a two-dimensional system. There are some data for the rise in temperature $\Delta\theta$ with time. Since $\Delta\theta \sim Q^{2/3}$, then

if, for plumes one can represent the increase in time by an exponential it follows that
$\Delta\theta \sim e^{t/\tau}$ where the doubling time is 0.69 τ and
and $Q \sim e^{3t/2\tau}$ where the doubling time is 0.46 τ and τ.

Data are not sufficiently extensive nor repeatable, see Table 5 to define an exponential but a "τ" of order 10 - 15 sec is plausible. This makes a doubling time for Q of 4 - 7 sec. There is doubt as whether it is appropriate to attempt to fit exponentials to those transients especially as there is no well defined consistancy between temperature rise and flame length data but given the above approximation, a doubling time of 4 - 20 sec appears to be an order of magnitude estimate for heat release in these experiments. Although the raw data are not a very good basis for estimating doubling times it would appear there could be a substantial difference in the estimates (a three-dimensional treatment being more likely). This is a reflection perhaps of the inadequacy of the simple relations based on stationary sources. Further development of theory may be required.

A FIRTO report [7] describes 13 fire tests comparing the efficiency of various sprinkler systems on fires. Two different types of pallets were employed with storage heights 1.75, 2.2., 3.2 and 5.2 m. The cardboard cartons were 55 cm x 45 cm x 38 cm high filled with about 0.5 kg of polystyrene chips. The ignition was at one position on the face of a stack (1.7 m from a target). Some data - not reported - were obtained on pressure, oxygen concentration and air velocity. The rises in temperature are recorded and results from the report graphs give mean rates of rise which vary from 1.5 °C/sec to 6°C/sec.

These give data which show a doubling time (for temperature rise) of about 70 secs.

Other tests show a linear rise after a delay of order 100 sec.

The time for flames to reach the top of the first level and the top of the stack are given for every test. Vertical and horizontal spaces were 200 mm for post pallet fires and 150 mm vertical and 100 mm horizontal for the free standing pallets. Stacks were not always an integral numbers of pallets high. One test for which there are photographs consists of two whole pallets each containing 3 levels of boxes with one box above it. Another test had one pallet of 3 boxes with 2 boxes above. One deduces the height to the top of the first pallet as approximately 1.45m. We then have in Table 5 the mean time for each test for flames to travel from this level to the top of the stack (it was always before the 1st sprinkler opened) and its distance.

Table 5

Type of Stack		Stack heigth less 1.45 m	Time sec	cm/s	Comments
Post Pallet 200 mm wide	1	3.75	103	3.61	No correlation between mean speed and stack height
	2	0.30	11	2.8	
	3	0.30	20	1.4	
	4	0.75	29	2.6	
	5	1.75	45	3.9	
	6	0.75	40	1.9	
Free Standing 150 mm	7	1.75	10	17.5	
	8	1.75	45	3.9	
	9	3.75	47	8.0	
	10	1.75	70	2.5	
	11	1.75	60	2.9	
	12	1.75	77	2.2	
	13	1.75	59	3.0	

It is not possible to associate variability with the choice of pallet design, pallet height or pallet gap. Values for free standing pallets overlap with those for post pallet racks.The mean speeds are of order 3 cm/s.

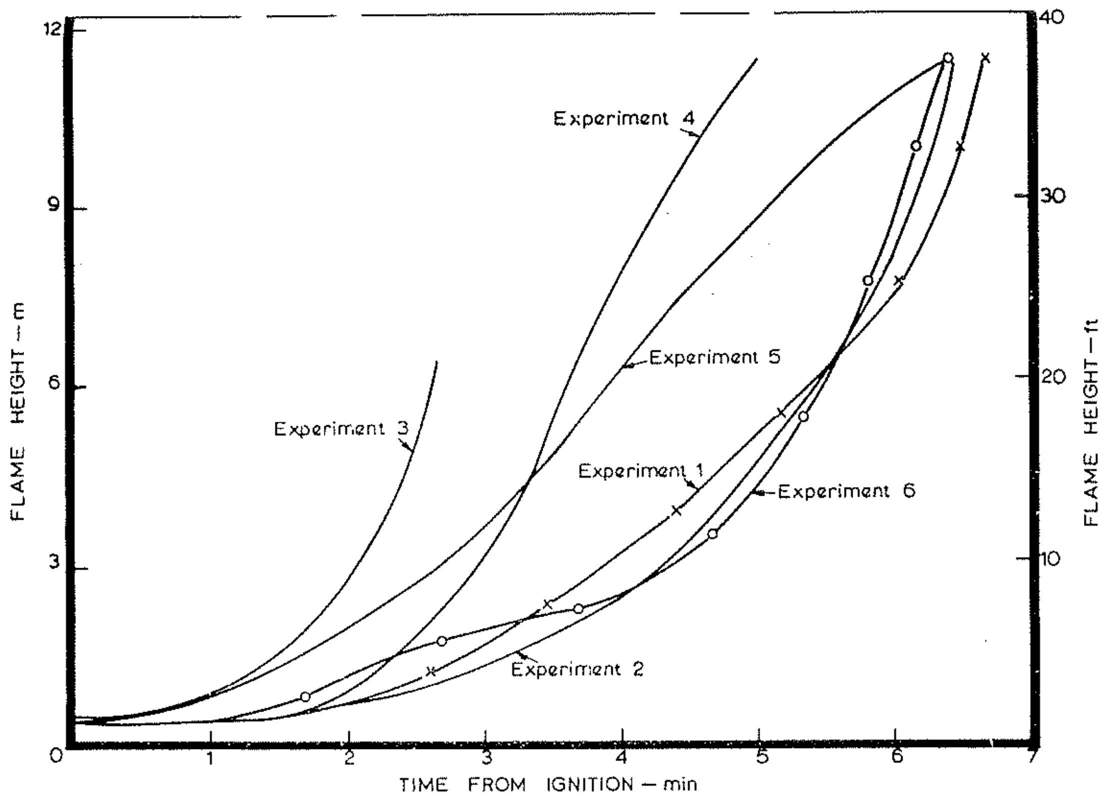

Fig. (1) Increase in flame height - experiments 1-6; Ref [3]

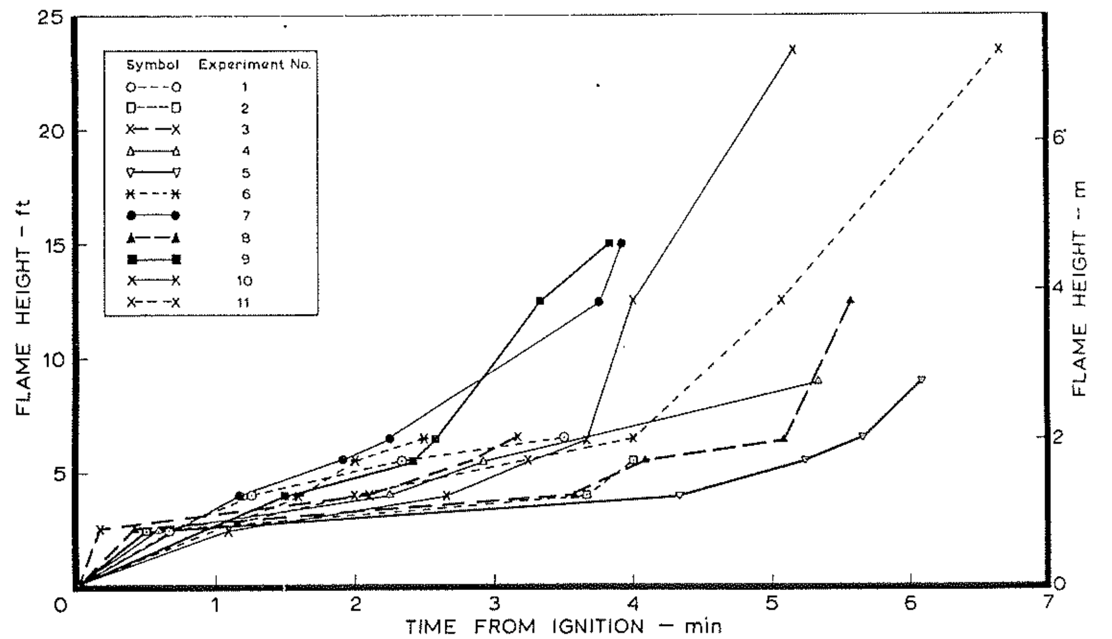

Fig. (2)Rate of flame development; Ref [3]

6 Video recording and sideways spread

Only one video of a FIRTO test has been studied. There are problems owing to lack of alignments, lack of height markings if one seeks to make measurements from it but certain observations seem significant.

1. If a box overhangs another the exposed edge is vulnerable to convective heat.

2. There is a tendency for flames to spread sideways in transverse gaps.

As soon as any horizontal gap has a horizontal gradient in temperature there will be a low level flow towards the low density region and a high level flow from it. There are two processes responsible:

1) any back pressure preventing free acceleration upwards leaves some buoyancy unbalanced by acceleration i.e. some hydrostatic pressure and this causes the flow described above

2) turbulent diffusion takes air into the rising stream and combustion products out of it - in a manner having similarities to the process of entrainment into a rising plume as in Fig (3).

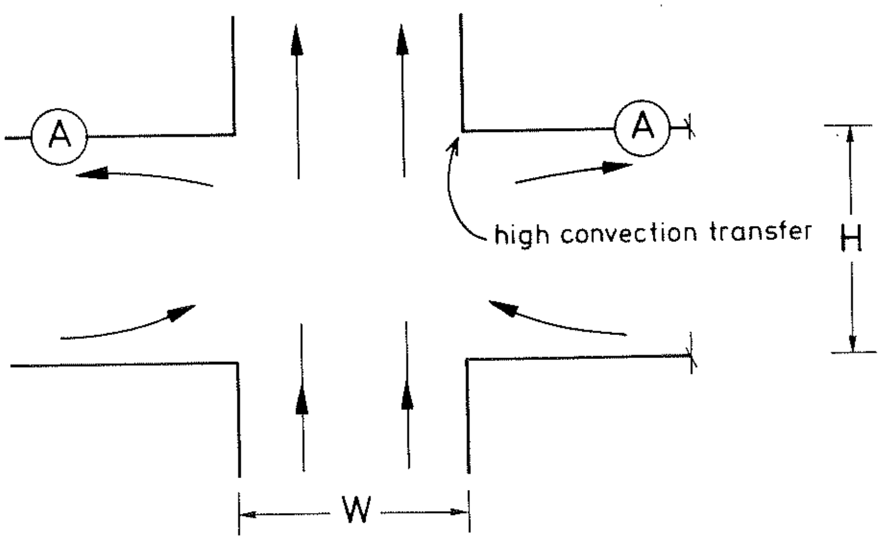

Fig (3) Scetch of flow pattern

Times of spread horizontally are perhaps 2-3 times longer then in vertical spread, but spread is in two directions at more than one level and almost out of range of any water droplets (except perhaps the smallest in size).

It is not clear what the process of flame spread is. There is some evidence that there is a process similar to one or other kind of flashover, e.g. (1) spread under the "ceiling" which ignites the "floor", or (2) heating by combustion products to raise "ceiling" and "floor" to a temperature at which flame spreads quickly across.

The process of sideways spread might be expected to proceed as follows: some combustion products heat the lower surface (A) and spread sideways. However vitiation of the local atmosphere may inhibit flame spread until the buoyancy is sufficient to cause enough circulation to bring in oxygen. This means that flames may not appear until enough hot and flammable gases have spread to a nearly vertical flue. One can see examples of fast upward spread into a neighbouring vertical flue - presumably the result of preheating by unignited hot gases.

7 Flame height and spread rate

The "simple" theories of flame spread in which the effect of the flame is respresented by a thermal flux eg. those of Saito, Quintiere & Williams [8] (and the developments by Thomas and Karlsson [9] and by Hasemi [10, 11]) cannot readily be adapted to vertical spread in a cavity. The effect of thermal expansion is possibly significant and some simple experiments should be undertaken to test these speculations. The essential feature of the experiments is the introduction of holes into the cavity walls and base. Although this reduces the mean heat production capacity the holes on the sides will have a significant effect on the effect of thermal expansion.

A simple flame length theory for flame in a gap is not possible as a simple extension of conventional flame length theory except initially; some provision must be made for restrictions in oxygen entrainment. A purely two-dimensional treatment could only permit oxygen (air) to enter the system from <u>below</u> the fire or from the sides.

In high rack storage gaps exist near the floor and one speculates that initially at least this is a low resistance part for air flow to the fire.

8 Conclusions

1. The data reviewed were obtained for purposes other than those of interest in the study of fire growth.

2. The main observations recorded concerning the rise of the flame tip show considerable variation. Much of this appears to be associated with the ignition place, and the delay before the fire begins to grow. There are subsequent variations in the passage of flame from the top of level 1 to the top of level 2.

3. Flames on the outer face of a stack of cardboard boxes have an average speed of order 1-3 cm/sec and in the flue between two boxes about 10 cm/sec.

4. Sideways spread through horizontal gaps is inherent in the process of fire growth in high racked goods.

5. There is evidence that the width of the vertical gap affects speed but the data (for 75 mm, 100 mm, 150 mm) gaps are not from the same set of data and have different ignition sources.

6. There are too few data to establish whether spread is exponential but it does appear to accelerate and, if exponential spread is assumed, the linear doubling time in a vertical gap (flue) is roughly 30-60 sec and hence that for heat release is of order 10-40 secs - depending on the assumption about flame geometry. If the flame length is assumed to increase linearly with heat release (as it might if friction on the cardboard surface is significant) then the doubling times for the flame length are of order 30-60 secs.

7. Experiments need to be done with different gaps at floor level to see how significant there are in controlling the essential air supply with a distribution of small holes in the vertical side to access the role of thermal expansion and sideways entrainment.

Acknowledgements

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References

[1] Young, R.A.: Fire Tests with Sprinklers on High Piled Stack", Fire Research Note No 814, Fire Research Station, Borehamwood, 1970.

[2] Nash, P., Bridge, N.W. & Young, R.A.: Some Experimental Studies of the Control of Developing Fires in High Racked Storages by a Sprinkler System, Fire Research Note 866, idem 1971.

[3] ibid: Experiments with Sprinklers in High Racked Storages: Extinction with Face-mounted Sprinklers, Fire Research Note 914, idem 1972

[4] ibid: Experiments with Sprinklers in High Racked Storages: Extinction with Centrally mounted sprinklers, Fire Research Note 916, idem 1972.

[5] Field, P., Fire Surveyor, pp.9-24, October 1985.

[6] Alpert, R. & Ward, Fire Safety Journal, I, 127(1984).

[7] The Protection of High Piled Storage with Sprinklers, FIRTO Technical Evaluation Report, TE2187, F.I.R.T.O. Borehamwood, 1984

[8] Saito, K., Quintiere, J.G., Williams, F.A.: Proceedings 2nd International Symposium on Fire Safety Science, Hemisphere Publishing Co., p.75, 1985.

[9] Thomas, P.H., Karlsson, B.: On Upward Flame Spread, Department of Fire Safety Engineering, Lund, Sweden, LUTVDG/TVBB-3058, p.22, 1991.

[10] Hasemi, Y., Fire Science and Technology, p.75, 4(1984).

[11] ibid, Proceedings First International Symposium on Fire Safety Science, Hemisphere Publishing Co., p.84, 1985.