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THE FIRESTORM - ITS SIZE AND IMPORTANCE

by

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1. INTRODUCTION

This paper is concerned with an aspect of extensive city fires which is nowadays usually associated with war time conditions, namely the fire storm. The best known examples, perhaps, are those which occurred in fires initiated by heavy bombing raids on German cities during World War II, especially Hamburg in July 1943, which resulted in heavy loss of life, although there are reports of fire storms in many great historic fires including, for example, the Great Fire of Konigsberg in 1764. The term "fire storm" is often used subjectively by people who have experienced the conditions occurring in one, and it appears from their description that the distinguishing characteristic of the fire storm is a high wind, in many cases reported to be of hurricane force. Observers also report high intensities of radiation, but these are characteristic of all large fires.

War time fire storms followed bombing attacks in which a high proportion of the buildings in a large area were set on fire within a short space of time; these conditions may well follow the explosion of nuclear weapons, and this has led to considerable civil defence interest in the fire storm. It is now more than 20 years since the violent fire storms of World War II, but the passing years have tended, in many ways, to obscure rather than clarify our concept of the fire storm. This paper is an attempt to assign a definite meaning to the term, to show that a fire storm is a consequence of the interaction of a large number of fires, irrespective of meteorological conditions, to evaluate as far as possible the wind conditions in a fire storm area, and to provide some rational basis for the prediction of the minimum area of fire in which fire storm conditions can occur in a given type of built-up area.

2. OCCURRENCES OF FIRESTORMS

2.1. PEACETIME FIRESTORMS

There are many reports of high winds occurring in conflagrations[17], and it appears that the firestorm had been known for some years previous to World War II and is a characteristic of many extensive city fires. Thus Rumpf[2] in 1932 describes the firestorm in much the same terms as observers of World War II. In particular he quotes some examples of firestorms occurring in historic conflagrations, as described by contemporary observers:

(i) <u>Great Fire of Konigsberg, 1764</u>

"The steadily rising wind storm caused an endless rain of fire."

"Wind blew firemen's water jets sideways, transforming them into a fine drizzle which did not even reach the fire."

According to the account given the fire appears to have included many large buildings and blocks of warehouses, etc.

(ii) <u>Hamburg, 1842</u>

"The firestorm which raged up the Bergstrasse..."

(iii) <u>Chicago, 1871</u>

"The windstorm produced by this sea of fire acted like a pair of huge bellows on the fire."

(iv) <u>Baltimore, 1904</u>

"Ten minutes after this explosion twelve great massive buildings were alight, set on fire by burning brands carried by the hurricane-like draughts caused by the fire."

2.2. WARTIME FIRESTORMS

2.2.1. A description of a wartime firestorm

Many accounts have been given of the firestorms during World War II, and for a more complete exposition these should be consulted. The description given here is a summary of experiences related by eye witnesses[12, 13] and is included in the present paper for the sake of completeness. Except for Hiroshima and Nagasaki, the firestorms occurred usually in attacks in which incendiary and high explosive bombs were alternated. The latter caused structural damage and the incendiary bombs ignited the combustible contents. Often the water mains were damaged and fire-fighting otherwise disorganised. The fires were thus allowed to develop unchecked, and the absence of roofs and windows exposed the combustible material to burning brands and radiation, so that the fire spread rapidly; within 20 minutes of the dropping of the first bomb extensive areas were transformed into a sea of flame and the firestorms began. The firestorm reached its climax in 2 - 3 hours, raging at its full force for about 3 hours, and the flames began to die down 5 - 6 hours from its beginning[12, 13, 20 etc.]. All the combustibles within the area were entirely consumed by fire.

Within the fire area extremely high winds were experienced, throwing over vehicles and men, tearing off roofs, uprooting trees and blowing through burning buildings, thus filling the streets with flames and sparks, fanning the fires and inhibiting the movement of personnel. There was a high mortality probably because of the intense heat and because clothing was ignited. The only means of escape, other than in the initial stages of the fire, when many were rescued by the Fire Brigade, appears to have been by the use of water to dampen clothing, and by crawling through the fierce storm on hands and knees.

2.2.2. Occurrence of wartime firestorms

Table I gives details of some major fire raids on Germany of World War II, together with the areas of concentrated damage, mortality and bombing density where these data are available. Fires in Japanese cities are not included in the table because of insufficient data.

TABLE 1. OCCURRENCES OF FIRESTORMS IN GERMANY IN WORLD WAR II

Place	Date of attack	Area destroyed ($mile^2$)	Percentage of population of destroyed area killed	Maximum bombing density on 1 km square tons/sq mile[14]	Comments
BERLIN	-	½ $mile^2$ (1 km^2) (Böttcher[6])	-	-	Small or partial firestorm (Magnus and Leutz)[6] No firestorm[5] (Brunswig)[6] *
BREMEN	-	-	-	-	One small area fire burned rapidly under firestorm conditions[6]
BRUNSWICK	14/15 Oct 1944	(1.02 $mile^2$) (655 acres[10])	0.7		Medium strength firestorm after about 4 mins.[10] Furniture sucked up by tornado, violent dust devils, showers of sparks and burning embers[10].
COLOGNE	30/31 May 1942[5]	1.04[5]	0.6 (3200 deaths)	90	Firestorm (Leutz)[6] No firestorm[5][14] (Brunswig and Magnus)[6]
DARMSTADT	11/12 Sept 1944	1.5[1][5]	21 (17)	-	Firestorm emerged after 1 hr and after 2 hrs wind speed Force 10-12 and subsided after 4 hrs.[10] Firestorm[1][5][10]. No firestorm (Brunswig)[6]
DRESDEN	13/14 Feb 1945	8-11 sq miles[10]	- (13)	-	Firestorm[1][5][6][10]. Damage did not approach that of Hamburg (Brunswig)[6] Violent firestorm[10]
HAMBURG	24/25 July 1943	1.5[1][12]			No firestorm. Street frontage 54 miles[12]
	27/28 July 1943	5.1[1][12]			Firestorm (general) Street frontage 133 mile[1][12]. Generally accepted as the most severe fire in Hamburg.
	29/30 July 1943	2.2[1][12]			Firestorm[13]. No firestorm (all others). Street frontage 104 miles[1][12].
	Totals	55-60%	15 (22)	190	

* Ref. 6 is a recent collection of data and observations by wartime German officials and engineers. The name in brackets here refers to the originator of the information.

TABLE I (continued)

Place	Date of attack	Area destroyed (mile^2)	Percentage of population of destroyed area killed	Maximum bombing density on 1 km square tons/sq mile[14]	Comments
HEILBRON	4 Dec 1944	-	-	-	Probably firestorm (Brunswig)[6]. Probably no firestorm (Magnus)[6]
KASSEL	22/23 Oct 1943	2.9 (1) 3.1 (5)	6.2 (10)	240	Firestorm[1][5][10] (Leutz)[6]. Probably no firestorm (Brunswig and Magnus)[6]. Firestorm within 30 minutes and centre partly evacuated before raid[10].
KREFELD	21/22 June 1943	-	-	70	No firestorm.
LEIPZIG	-	-	2.2	-	Firestorm[8]
LÜBECK	-	-	-	-	First mass fire in Germany in World War II. Probably approached firestorm conditions[6].
MANNHEIM	1 Mar 1945	-	-	-	Probably no firestorm[6]. One block burned under firestorm conditions in summer 1943 (Brunswig)[6]
PFORZHEIM	-	-	-	-	Firestorm (Magnus)[6]. Probably firestorm (Brunswig)[6] No firestorm[5] Leutz[6]
STUTTGART	19 Sept 1944	-	0.6	-	Fire storm[14]. No firestorm[5] (Magnus)[6]

TABLE 1 (continued)

Place	Date of attack	Area destroyed (Mile^2)	Percentage of population of destroyed area killed	Maximum bombing density on 1 km square tons/sq mile[14]	Comments
WUPPERTAL	3 May 1943[5]				Firestorm[15] (Leutz)[6]. Probably no firestorm (Brunswig)[6]
- BARMEN	29/30 May 1943[1][10]	1.0[15]	4.5	190	No firestorm[1][5] (Magnus)[6]
-ELBERFELD	24/25 June 1943[15]	2.0[15]			
WURZBURG	-	-	-	-	Verbal reports of firestorm still persist[6]

It can be seen that there is a wide diversity of opinion as to whether or not firestorms occurred, although some authorities are merely reflecting the opinion of others. Those cities which are generally accepted to be the scene of a firestorm are Hamburg (27/28 July), Kassel, Darmstadt and Dresden.

Some explanations of this diversity of opinion may be sought by considering the areas of fire involved in the firestorm. It appears from the somewhat sparse data on peacetime fires that the area of fire necessary to induce firestorm winds is considerably less than the extensive areas reported in Table I. This is supported by Rodden et al[16] who assert that the smallest area of fire in which wartime firestorms have been observed is ½ sq. mile. Furthermore, because of the many parks and open spaces that occur even in heavily built-up areas, it is unreasonable to suppose that the fires in the firestorm areas formed one huge area of fire. Rather, one may expect a number of large area fires, each inducing a firestorm within its own area. This view is supported by the Reports of the Police President of Hamburg[13], which states "Tens of thousands of individual fires were joined in a very short time into major area fires, which caused firestorms of hurricane force." (July 27/28) "This raid (29/30 July) too caused devastating and extensive area fires and firestorms..." "...this huge firestorm caused by the blending of a great number of firestorms." It is also notable that accounts of the effects of the firestorm do not vary from one city to another, in spite of the differences in area involved. The wide diversity of opinion with regard to the existence of firestorms may well be due to the relatively small area necessary for the existence of firestorm conditions. Thus in a relatively small proportion of the area, a firestorm may develop, unnoticed in a larger proportion of the area, and hence by the greater part of the community. Post fire reports would then contain a diversity of opinion with regard to conditions in the fire, a few reporting firestorm conditions, the larger proportion not.

The bombing density is included in Table I because it is directly related to the initial fire density, the number of fires per unit area. Stanbury[7] points out that in cities where firestorms developed the bombing density was of the order of 200 tons per sq. mile whereas in other fire raids the density was 70 tons per sq. mile. Since the fire density is directly proportional to the bombing density, this implies a high initial fire density in firestorm attacks. Reports state that in Hamburg 2 out of every 3 houses were on fire after 20 minutes[13]. Stanbury estimates the initial fire density was 2,500 fires per sq. mile or about 50 per cent of the buildings. These initial fires then spread to include all buildings.

The figures on percentage of deaths are obtained from figures in the reports of U.S.S.B.S.[3], with the assumption of an even distribution of population over the entire area of the city. The figures in brackets are estimates obtained by Rodden et al[16]. These statistics are included to illustrate how lethal these fires were - U.S.S.B.S.[3] estimate that 70 - 95 per cent of the casualties were due to effects other than blast from high explosive.

3. DEFINITION OF FIRESTORM

The firestorm has been a recognised characteristic of city fires for hundreds of years, but its essential features have tended to be obscured in recent years by the many other severe effects related to area fires. Reports of firestorms in historic fires quoted above refer only to the force of the wind, and Rumpf[2] quotes Siegart's picture of a firestorm "...when the individual fires begin to meet and merge into one another, and when the heated air, together with the flames shoot upwards as though through some huge chimney stack, and when the hot air, as it rises, sucks up the cold air nearby, thus fanning the smaller fires."

Essentially, a storm is a name given to a wind force (see Section 4), a firestorm is a storm of wind induced by the fire. This leads, and has led, to confusion: the fires in which firestorms have occurred have frequently been themselves identified as firestorms. It is proposed that firestorm conditions at any point of a given fire area may be defined in terms of a wind velocity at that point. We thus make the following hypothesis:-

(i) Firestorm conditions exist at a point of a fire area when the fire-induced wind speed at that point exceeds some critical value, u_c.

(ii) The definition of an area of urban fire as a firestorm area is not so straightforward. One may take the view either that a firestorm area exists when firestorm conditions exist at some point of the fire area, and since the maximum velocity will occur at the perimeter of the fire, this implies that the velocity of the wind at the perimeter, u_p, exceeds u_c, or alternatively, that a firestorm area exists when firestorm conditions exist over a high proportion, say one half, of the fire area. Formally:

(a) A firestorm area is an area A_1 of an urban fire in which $u_p \geqslant u_c$, or

(b) Let A_2 be the total area of fire, and let A_f be the area of that part of A_2 in which firestorm conditions exist. Then A_2 is a firestorm area when $2A_f \geqslant A_2$.

The two latter definitions are quite arbitrary, but they may be interpreted in a comprehensible manner. In the first case firestorm conditions would only be observed by firefighters and onlookers on the perimeter of the fire, and in the second case, firestorm conditions would be observed by a high proportion of the population of the fire area.

4. EVALUATION OF u_c

The definition of firestorm conditions of paragraph 4 demands that some numerical value be assigned to the parameter u_c. This will now be evaluated by considering the values of windspeeds implied by existing firestorm reports.

4.1. METHOD OF ASSESSMENT

For obvious reasons no measurements were made during the wartime firestorms of windspeeds, intensities of radiation or other fire characteristics. However, there are a number of eye witness[12, 13] accounts describing the effects of wind on objects and personnel, and from these and other data some numerical estimates may be obtained of conditions in the fire area. This technique is not unknown, and is widely employed by some Meteorological observers, who, lacking sophisticated instrumentation, use the Beaufort Scale to estimate wind force by observing the effect of wind on smoke, leaves, trees, etc.

4.2. WIND SPEED DATA

For convenience, Table II gives the Beaufort Scale for high wind speeds, together with effects of wind on land.

Table II. A selection from the Beaufort Scale of Wind Force

Force No.	Windspeed - m.p.h.	Description	Effect on land
8	39 - 46	Fresh Gale	Twigs broken off trees, progress impeded.
9	47 - 54	Strong Gale	Slight structural damage occurs, chimney pots and slates blown off.
10	55 - 63	Whole Gale	Trees uprooted and considerable structural damage.
11	64 - 75	Storm	Widespread damage, seldom experienced inland.
12	75 +	Hurricane	Wind of this force only involved in tropical revolving storms.

Below are listed some of the many effects of wind observed in firestorms described by eye witnesses and others[1,3,9,10,12,13,20] and a probable wind speed is estimated by reference to Table II or to other data obtained from the Meteorological Office[18,19].

1. Walking against wind impossible. Walking against the wind is difficult at Force 8 and for most people likely to be impossible at Force 9, for all at Force 10.

2. People thrown along the ground. No definite information is available except that this is probably very rare and happens only in hurricanes (Force 12 and above) and on mountains. There is a report of one person thrown over on a mountain at a velocity calculated to be of the order of 90 m.p.h. Force 12 seems to be a likely value.

3. 3ft. diameter trees torn up. Whether or not mature trees are uprooted depends on the type of soil, its state at the time, exposure, type of tree, its age and many other factors. However, large areas of forest were destroyed in Scotland on January 31st 1953 (Force 10 or 11) and a considerable number were uprooted in Yorkshire on February 16th 1962 (Force 9 or 10), where extensive damage to trees 30 - 40 ft high was recorded.

4. Large branches torn off trees. Force 8 will break off twigs and small branches, so it is not a large extrapolation to antici pate that Force 9 winds would be capable of breaking off larger branches.

5. Cars, lorries, etc. overturned. Pantechnicons were overturned near Doncaster on November 1st, 1965 (Force 8 - 9). On February 27th 1966 a train was blown off a viaduct in Lancashire. (Force 10).

6. Window panes blasted. This depends very much on its location in the building, its size, shape, and thickness, as well as the geometry of the building itself. In some modern tall buildings window breakages occur at Force 7 - 8.

7. Roofs torn off. This depends very much on the pitch of the roof and its construction, flat or low-pitched roofs being subject to much higher loadings than steeply pitched roofs. On November 4th 1957 roofs were removed from new houses at Hatfield (Force 8 - 9), but these were low-pitched and there was some doubt about their fastenings. Roofs were removed from schools in Northern Ireland on September 16th 1961 (Force 10) and in Leeds on November 1st 1965 (Force 8 - 9). It seems likely that some roofs, especially low-pitched, lightweight ones, may be torn off in a Force 8 - 9 gale, but more conventional roofs are not likely to be torn off until speeds reach Force 10.

8. Other wind effects. Tables, doors, etc. thrown along streets, crowns of young trees blown to the ground - no information.

4.3. ASSESSMENT OF u_c

It appears from the data reviewed in 4.1.2. that the damage to structures and effects on personnel in the firestorm areas of World War II are those normally associated with a wind force in excess of Force 10 - 11.

Thus the wind force in the definition of firestorm conditions could well be considered as compatible with the Beaufort definition of the storm as a wind of Force 11, i.e. u_c = 70 m.p.h.

It should be realised that the assessment of the data in 4.1.2, although in general, from reliable measurements, depends very much on local conditions. Furthermore, the wind force quoted is a mean figure, and gusts have been observed in many parts of the British Isles ranging between 30 - 100 per cent of the mean windspeed. Thus in the reference cited to "Gales in Yorkshire", although the recorded mean windspeed in Sheffield was 46 m.p.h., the maximum wind speed recorded was 97 m.p.h. Hence a Force 10 wind may well be associated with gusts in excess of 100 m.p.h.

5. CONDITIONS UNDER WHICH A FIRESTORM MAY OCCUR

5.1. EMPIRICAL CRITERIA

By a survey of the values of certain parameters in known firestorm areas, Rodden et al[16] have derived a set of minimum conditions which, it is asserted, must all be met before a firestorm may occur. These conditions are as follows:

Fire load density	8 lbs/ft^2 of fire area.
Fire density	50 per cent of the structures on fire simultaneously.
Surface wind	8 m.p.h.
Firestorm area	0.5 sq. miles.

This list also included a comment on atmospheric stability.

Bond[27] postulates that the building density must exceed 20 per cent in order that a firestorm may occur. This value seems rather low in view of the known characteristics of German cities reviewed in 6.3.

These empirical criteria may or may not give an indication of the minimum conditions under which a firestorm may occur, but they certainly have no physical basis at present. An attempt will be made in the following paragraphs to calculate conditions for a firestorm from known physical data.

5.2. THEORETICAL CRITERIA

The problem of predicting the occurrence of a firestorm is twofold. The following must be calculated: Firstly, under what conditions a firestorm exists, and secondly, what minimum initial fire configuration will spread to meet these conditions? The present paper is concerned with the first problem.

5.2.1. A theory of the firestorm

The definition of the firestorm proposed in Section 3 leads to the consideration of means of calculating the windspeed in the streets in the fire area. Each fire as it burns entrains air, and the total air requirements of the fires must be drawn from the atmosphere outside the fire. Because of the mass of hot rising gases above the roofs, when the fires are close enough together it is difficult for air to be drawn from above and air must be drawn towards the fires horizontally, being channelled through the streets, thus increasing the windspeed.

Clearly, whether or not air can be drawn from above depends largely on the spacing of the fires, the nearer they are the more difficult it becomes. This assertion is supported by the observation that fuel beds, burning separately, give flames which tend to merge together, because of the pressure gradients induced by restriction to lateral air [22, 23] flow. The separation at which this occurs has been calculated [22,23] and will be discussed further below. When the fires are far enough apart, air may be drawn from all directions, and each building behaves approximately as a point source since the plume above the fire entrains relatively little air. It can then be shown that firestorm conditions would not develop in the areas listed in Table I.

5.2.2. Entrainment of air

The rate at which a building fire entrains air depends on the stage of development of the fire. In the early stages, where only single compartments are on fire, the mean velocity of entrainment of air over the window area is given[29] by

$$\bar{v}_e = 0.14 \left(\frac{g\,\theta_{fl}}{T_{fl}} H_w \right)^{\frac{1}{2}} \qquad \ldots\ldots (1)$$

where H_w is height of the window θ_{fl}, T_{fl} are the temperature rise of the flame above ambient and its absolute temperature. At a later stage in the fire, when compartment walls and floors have failed, the mean entrainment velocity over the window area is

$$\bar{v}_e = 0.565\, S_n \left(\frac{g\,\theta_{fl}}{T_{fl}} H \right)^{\frac{1}{2}} \qquad \ldots\ldots (2)$$

where $S_n = \frac{1}{n^{3/2}} \sum_{i=1}^{n_s} \sqrt{i}$; ($S_n \sim 0.7 - 0.8$, $n_s > 3$)

and n_s is the number of storeys, and H is the height of the building. Both of these formulae are calculated by assuming the compartment or building to be full of hot stagnant gas, and in the latter, an even distribution of windows.

The entrainment in the later stage is considerably larger, and the time taken for transition from one stage to the other is approximately the mean fire resistance of the compartment boundaries. This might well correspond to the 2 - 3 hour growth period observed in the wartime firestorms [12, 13]. The aerodynamic behaviour of the flames in the later stage is also very different, any applied pressure gradient across the building causing the flames to be deflected out of the building, behaving as a free burning fire. The mean entrainment velocity over the surface area of flame is then[24]

$$\overline{v}_e = 0.054 \left(\frac{g \, \theta_{fl} \, L}{T_{fl}} \right)^{\frac{1}{2}} \qquad \ldots\ldots (3)$$

where L is the flame height which is comparable with Equation 2 for ventilation of openings of 20 per cent when H = L and Equation 2 is averaged over the entire vertical area of the building front.

5.2.3. Theoretical model of the firestorm

We now develop a simple theoretical model of a fully developed firestorm. It will be assumed that the initial fires have spread so that all buildings are alight, and sufficient time has elapsed so that the compartmentation of the individual buildings has failed. Since entrainment is a maximum at this stage, this model represents the most likely situation in which firestorm conditions could occur.

In high building density cities the unit of building is the building block, the development of which is described in some detail by Bird[1]. The area of the block is almost entirely covered by buildings, with narrow streets and few openings to the surrounding streets. When all the buildings in the block are on fire, the building block may be regarded as a single area fire, especially from the point of view of calculating entrainment, since, because of the lack of external openings, only the outer surfaces of the building block need be taken into account. Inspection of maps indicates that over quite extensive areas, the building blocks form approximately a rectangular street plan. The idealised model considered here will thus consist of an array of square fuel beds, arranged on a rectangular street plan. This model is not expected to be representative of all cities, nor will it be adequate to describe all physical processes, but in the context in which it is required it is expected to give a reasonable representation of airflow in German cities.

5.2.4. Conditions for a fully-developed firestorm

On the basis that firestorm conditions occur when the wind velocity in the streets exceeds a certain value, the calculations described below are aimed at determining the air velocity in the streets of the fire area. Flames from separate fuel beds, when placed sufficiently close together, give flames which merge together and form a canopy of flames over the streets[22, 23]. In these circumstances, downdrafts are considerably inhibited and the air required by the flames must travel down the streets between the fuel beds. The fluid flow problem now posed is that of a number of finite sinks drawing air horizontally from the surroundings.

The velocity field in the fire area may be determined as a problem in potential flow, but in view of the limited accuracy required and the uncertainties in some of the quantities to be estimated, this degree of sophistication seems unjustified at this stage. Suppose, as an approximation, that the flow is the same in all the streets between fires which belong to the same ring, considering the fire area as consisting of a system of concentric rings of fuel beds about the centre of the fire. Then it can be shown[23] that the onset of merging occurs when

$$\left(\frac{S}{D}\right)^3 = 4K^2 \left(\frac{L}{D}\right)^2, \quad K = 0.054 \qquad \ldots\ldots. (4)$$

where D is the linear dimension of a fuel bed, S the separation of fuel beds, and L the height of the flames. The average velocity of the perimeter is then given by

$$u = n \frac{D}{S} \bar{v}_e = K' \, n \frac{D}{S} \sqrt{gL} \text{ from Equation 3}$$

where $K' = K \left(\frac{\theta_{fl}}{T_{fl}}\right)^{\frac{1}{2}}$ and $n = N^{\frac{1}{2}}$

and N is the number of fires.

$$K' \, n \frac{D}{S} \sqrt{gL} \geqslant u_c \qquad \ldots\ldots (5)$$

Suppose an area fire occurs in a city with given building characteristics. Then putting $n D = \dfrac{A}{1 + \frac{S}{D}}$ in Equation 5 where A is the area of the fire gives the condition for a firestorm

$$A_1 \geqslant \frac{1}{K'^2} \frac{u_c^2}{gL} S^2 \left(1 + \frac{S}{D}\right)^2 \qquad \ldots\ldots (6)$$

For a firestorm to occur in more than half the total area of fire, the area A_2 must obey the inequality $A_2 \geq 2A_1$ (see Section 3).

6. BUILDING CHARACTERISTICS

The calculations of paragraph 5 show that to make any numerical prediction of the size of fire in which a firestorm occurs certain data on the building characteristics of German cities must first be gathered together. At the same time, for the sake of completeness, and because of the possibility of comparing the German cities involved in firestorms with cities in other countries and continents, it is convenient to tabulate other building data not required in the calculations.

6.1. CONSTRUCTION OF GERMAN CITIES

German cities in general consisted of five types of building construction as follows:[25]

Zone 1. The city centre. This consisted of an "Old Town" with a congested medieval street plan, narrow streets and many old buildings mingled with shops and offices.

Zone 2. The residential area. This was built around the Old Town and consisted, in the inner portion, of thickly populated blocks of all types, slum to middle class, corresponding roughly to British terrace-type houses and flats. The outer residential area contained a small proportion of separate houses and villas, but the building density was rather high. There were often small industrial buildings in the centre of blocks.

Zone 3. The suburban area, with houses and blocks of flats at 20 to the acre.

Zones 4 and 5. Consisted of industrial buildings, communication, etc.

6.2. CONSTRUCTION OF BUILDINGS

Zones 1 and 2 contained 70 - 85 per cent of 19th Century buildings[26]. These were heavily constructed, with exterior brick walls averaging 1 ft 3 in thick, interior partitions 5 in to 10 in thick, and plain wood or mud-filled pugged floors, or light brick arch construction. The roof was constructed of wood covered with slate or tiles, and there were many heavy wooden beams. Brunswig[28] has analysed a block of buildings, and evaluates a fire load of 68 lb/ft^2.

6.3. BUILDING STATISTICS

Table III summarises the available data on building density, street widths, building heights, etc. It can be seen that data are rather scarce and uncertain, and there is some disagreement over the value to be assigned to some of the parameters. It is more or less universally accepted that buildings were on average about 5 stories high, that the average dwelling had a ground area of 1500 sq. ft., and that the zoning described in 6.1. is adequate. There is also some measure of agreement about street widths and layout.

There is considerable disagreement about the value of the building density, . Although the actual value of is not important from the point of view of the calculations described in Section 5, it is clear that the building block, taken as a unit of construction, will occur largely in areas of high building density. This question may be resolved to some extent by comparison with the building density of London, which has many similarities with German cities. Both are built on medieval street plans, both have undergone considerable rebuilding throughout their history, although building construction may differ in detail. It may well be that the building densities of the two, depending largely on street layout, are very similar.

Table III. Average Building Characteristics of German Cities

Source	Building density	Streets	Building height	Number of buildings	Average area of building	
Ministry of Home Security[25]	60 - 75 per cent	Medieval street plan with narrow streets.	-	-	-	City centre.
	50 - 55 per cent	Terrace type houses.	-	-	-	Inner residential area.
	40 - 45 per cent	Small proportion of separate houses.	-	-	-	Outer residential area.
	30 per cent	-	-	Houses and blocks of flats, 20/acre.		Suburban area.
Fire Effects[11] of Bombing Attacks. Fed. C.D. Admin.	40 per cent	-	3 - 5 storeys	-	1500 sq. ft.	Central Area - "old town".
	-	Rectangular street plans.	3 - 6 storeys	-	3000 sq. ft.	18th Century town.

Table III. Average Building Characteristics of German Cities (Cont'd.)

Source	Building density	Streets	Building height	Number of buildings	Average area of building	
Stanbury[7]	33 per cent	-	-	6000/sq. mile.	1400 sq. ft.	Overall figure.
U.S.S.B.S.[3]	-	55 - 75 ft wide with average of 60 ft, except in Old Town.	4 - 9 storeys, average 5 = 70 ft.	-	1500 sq. ft. for dwellings. 10000 sq. ft. for offices, etc.	Hamburg.
	40 per cent - Old Town	Central zone with rectangular street plan, wide streets and many open spaces. Streets 40 - 60 ft. wide. Main streets 70 - 100 ft. wide. Old Town 40 ft. down to 20 - 30 ft. wide.	-	-		Kassel, Dormstadt etc.
Brunswig[28]	43 per cent	-	5 - 8 storeys	-	Area of block of buildings 800 sq. ft.	Hamburg, study of one city block 800 sq. ft.
Magnus[6]	67 per cent	-	-	-	-	

The building densities of London are as follows[7]:

City	72 per cent
West End	53 " "
Closed residential	43 " "
Open residential	19 " "
Docks	18 " "

These figures are remarkably similar to the first group of figures in Table III, and the figure of 40 per cent for the centres of German towns given by other authorities seems rather low. It seems likely that this area did, in fact, have a much higher building density, more of the order of that given by the wartime Ministry of Home Security.

6.4. BLOCK STRUCTURE

There are no statistics available on the average size of building block in German cities, although some random measurements from maps of Hamburg seem to indicate a likely value of its linear dimension of about 400 feet. Some values may also be obtained indirectly from values of total street lengths in the fire area quoted in Table I. Assuming a rectangular street plan and blocks of comparable sizes, the linear dimensions of a square block D are then given in terms of the area involved A, the street frontage F, and the street width S by the equation

$$S + D = 4A/_{F}.$$

Substituting the values of F and A from Table I leads to the following values for Hamburg, which are probably representative also of other German Cities.

	$(S + D)$ ft.
Raid of July 24/25	590
Raid of July 27/28	820
Raid of July 29/30	450

Assuming a value of S of the order 80 ft leads to the conclusion that D lies approximately between 400 and 700 ft. Brunswig[28] gives an analysis of an area of buildings with linear dimension of 800 ft although it is not stated whether or not this is a building block.

7. EVALUATION OF FIRESTORM CRITERION (Equation 6)

The above data, although rather crude, allow some estimates of the firestorm areas to be made on the basis of the criterion developed in Section 5. Owing to the approximate nature of the model itself, the uncertainties in the definition of firestorm, and the ranges of values encountered for many of the physical characteristics of the areas involved, these calculations cannot be expected to give a very accurate estimate. However, the order of accuracy required for most purposes is no greater than the order of magnitude, and the figures and theories used should be sufficient to do this.

7.1. SUMMARY OF DATA

(i) Wind Speed. We take u_c as the wind speed characteristic of a Storm (Force 11), so that $u_c = 100$ ft/sec.

(ii) Linear dimension of buildings. $D = 400 - 700$ ft, and street widths are of the order of 80 ft.

(iii) Flame height. Thomas[24] has correlated flame heights by an expression

$$\frac{L}{D} \propto \left\{ \frac{\dot{m}}{\rho_A \sqrt{gD}} \right\}^{\frac{2}{3}}$$

where $\dot{m}$ is the rate of burning per unit area.

The mean rate of burning may be estimated, since Brunswig gives the fire load as 68 lbs/ft^2 (about 12 lbs/ft^2 for each storey), and the duration of the fire was approximately 5 - 6 hours. Thus $\dot{m} = \frac{68}{360 \times 60}$ lbs/ft^2 sec., and $0.15 \leqslant \frac{L}{D} \leqslant 0.2$, the limits being attained when D = 700 ft and D = 400 ft respectively.

Thus $80 \leqslant L \leqslant 100$ ft approximately, say 90 ft, which is comparable with the average building height of 70 ft.

7.2. **MERGING OF THE FLAMES**

Substituting the values of $\frac{L}{D}$ in Equation 4 gives the separation at the onset of merging

$$\frac{S}{D} \propto 0.1$$

which is of the same order as the value of $\frac{S}{D}$ derived assuming S = 80 ft, D = 400 - 700 ft, and within the order of accuracy of the data and theory, this value indicates that the flames are at or near the onset of merging. The theory developed above is thus applicable.

7.3. **FIRESTORM AREA**

Substituting the values of L, S and $\frac{S}{D}$ in Equation 6 leads to the minimum area of fire A_1 in which firestorm conditions can exist

$$A_1 = 0.4 \text{ sq. mile for a typical German city.}$$

A firestorm involving the greater part of the fire area thus occurs in a fire of area A_2, given by $A_2 = 2A_1 = 0.8$ sq. mile.

8. DISCUSSION

The results of the calculations carried out above indicate that a firestorm can exist in conditions similar to those of German cities in fire areas in excess of 0.4 sq. mile, which, in terms of wartime fires, is a relatively small fire area. This result is supported by Rodden et al[16], who give a minimum firestorm area of $\frac{1}{2}$ sq. mile, and it also explains the reports of high winds in many, relatively small, historic conflagrations and the disagreement about occurrences of firestorms in many of the wartime fires.

Equation 6 also indicates the relative importance of some of the characteristics of the fire areas in determining the occurrence of firestorms. For high density areas $\frac{S}{D} \ll 1$ and Equation 6 may be closely approximated by the inequality

$$A_1 \gg \frac{S^2\, u_c^{\,2}}{K'^2\, gL} \qquad \text{......} (7)$$

Thus having defined the value of u_c, in terms of the building characteristics of the area, the minimum value of A_1 is proportional to $\frac{S^2}{L}$, and hence the most important factor is the street width S. The value of L may be calculated from Thomas' single fire correlations[24], in which $L \propto (\dot{m} D)^{\frac{2}{3}}$, but there is little or no data on the value to be assigned to $\dot{m}$, the rate of burning per unit plan area of each building, or its variation with the characteristics of the building, and thus, for the time being, L must be regarded as an independent variable of the firestorm calculations.

Since the available data are rather coarse, and since Equation 7 is very sensitive to small changes in S, the estimates of the area A_1 cannot be expected to be very accurate. However, it should be pointed out that from the point of view of escape from the fire area, the average length of the escape routes will be approximately proportional to the linear dimensions of the fire area ($\propto SL^{-\frac{1}{2}}$) and this is also the dimension that would be used in assessing potential firestorm areas from maps. Thus this inaccuracy is not as important as it would appear, within the limits of the accuracy required. It is clear that considerably more data and theoretical evaluation is necessary before the validity of the simple theory presented above can be established, and in particular whether the scaling laws implied by Equations 6 and 7 are valid.

The firestorm has been defined as a storm of wind (Force 11) induced in the streets by the large air requirements of the many fires, and it is appropriate at this point to consider the effects of the firestorm on other fire characteristics, and to assess its importance in urban fires.

(1) The high wind increases the probability of the spread of fire both within and between buildings. Eye witnesses[12, 13] have described burning beams hurled along streets, and a high density of burning brands and sparks. Since the roofs and windows are likely to have been damaged or destroyed the chance of spread by brands supported by radiation is very high. The passage of wind through the buildings, dragging flames and sparks from the burning compartments through the corridors and door openings further increases the spread to previously unignited material, and by maintaining an ample supply of air to the burning fuel, ensures complete combustion of the fuel.

(2) The conditions in the streets, scorched by the intense radiation from the fires, are considerably aggravated by the high winds, which in Germany inhibited both escape from the area[12, 13] and firefighting[6, 9] and rescue operations. The flying brands and sparks ignited clothing and blew into unprotected eyes, and high winds often made progress possible only by crawling on hands and knees.

(3) Because of the large area of fire, unless a person is near the outer edge of the fire area, the direction of escape must be uncertain, and the choice of an escape route would tend to be random unless outside aid is given. In a panic stricken state most people would tend to move in the direction of the wind, particularly in a wind against which it is impossible to walk, and this would tend to lead them further into the fire area. It seems likely, therefore, that the firestorm is at least indirectly responsible for the high death rates observed in wartime fires in which firestorms occurred.

CONCLUSIONS

1. It is proposed that the term "firestorm" should be reserved for the high wind observed in many large area fires, and that firestorm conditions exist at any point of a fire area when the wind speed at that point exceeds a certain value, taken to be that characteristic of a Storm (Force 11 on Beaufort Scale), that is 100 ft/sec.

2. The value of the velocity defining the firestorm has been derived from a review of reports of wartime firestorms. The reported effects of wind on objects and personnel have been found to be consistent with a storm Force 10 - 11 (Beaufort Scale), which is high enough to impede

seriously both escape from the fire area and fire-fighting activities, and it may also increase the probability of spread of fire between buildings.

3. A simple theory of the fully developed firestorm has been derived in which the air requirements of the many fires are calculated from single-fire data. The wind speeds in the streets are calculated on the basis that, because of the mass of hot gas rising above the fire, the entrained air must be channelled through the streets. This assertion is supported by reference to calculations and data on the merging of flames. The theory leads to a criterion for the fully developed firestorm, in terms of the building characteristics of the fire area and the height of the flames.

4. Both theory and data from reports of wartime and peacetime firestorms suggest that the area of fire necessary for firestorm conditions to exist is considerably smaller than the very extensive areas destroyed by fire in some of the wartime fires.

REFERENCES

1. BOND, H. (Ed). Fire and the Air War. Nat. Fire Prot. Assoc. Boston, 1946.
2. RUMPF, H. Brandbomben pp. 148 - 178. E. S. Mittler & Sohn, Berlin, 1932.
3. United States Strategic Bombing Survey. European War. Reports Nos. 1, 2, 193.
4. United States Strategic Bombing Survey. Pacific War. Reports Nos. 1, 3.
5. BESSON, P. La Tempete de Feu. Editions France-Selections, Paris, 1958.

6. MILLER, C. F. and KERR, J. W. Field Notes on World War II, German Fire Experience. Stanford Research Institute, October, 1965.

7. STANBURY, G. R. Ignition and Fire Spread in Urban Areas following a Nuclear Attack. Scientific Advisers Branch, Home Office, Report CD/SA 121, September, 1964.

8. BOND, H. Wartime Firefighting. Nat. Fire Prot. Assoc. Quart. 48, 4 (Apr. 1955) 349 - 80.

9. RUMPF, H. Der Hochrote Hahn. E. S. Mittler & Sohn, Darmstadt, Germany, 1952.

10. IRVING, D. The Destruction of Dresden. William Kimber & Co., Ltd., London, 1963.

11. United States Civil Defence. Fire Effects of Bombing Attacks. Technical Manual TM-9-2. Washington, 1952.

12. Hamburg Fire-raids, July 24th to August 3rd, 1943. Material supplied by Ernst Burkhardt. Ministry of Home Security, R. & E. Dept. 1945. (Unpublished statements).

13. KEHRL, Maj. Gen. Report by the Police President and Local Air Protection Leader of Hamburg on the Large Scale Raids on Hamburg in July and August 1943. Translated by Home Office, London, 1946.

14. Home Office, Scientific Advisers Branch, London, 1948. C.D./S.A.2 (Classified).

15. EARP, K. F. Death from Fire in Large Scale Air Attack - with Special Reference to the Hamburg Fire Storm, C.D./S.A.28. Home Office, Scientific Advisers' Branch, London, 1953.

16. RODDEN, R. M., JOHN, F. I. and LAURINO, R. Exploratory Analysis of Fire Storms. Stanford Research Institute, California. 1965.

17. 100 Conflagrations since 1900. Nat. Fire Prot. Assoc. Quart. 2, 29, 1935.

18. Meteorological Office. Private Communication.

19. AANENSEN, C.J.M. (Ed). Gales in Yorkshire in February, 1962. Meteorological Office, Geophysical Memoirs No. 108, H.M. Stationery Office, 1964.

20. BRUNSWIG, H. Conflagrations and Fire Storms. VFDB Zeitschrift, 1951, 1 (1) (Jan) 3 - 12; Brandskydd, 1951, 32 (12) 178 - 83.

21. SIMMS, D. L. and HINKLEY, P. L. Protective Clothing Against Flames and Heat. Fire Research Special Report No. 3, H.M. Stationery Office, 1960.

22. THOMAS, P. H., BALDWIN, R. and HESELDEN, A.J.M. Buoyant Diffusion Flames: some measurements of air entrainment, heat transfer and flame merging. Tenth Symposium (International) on Combustion. Cambridge, England, 1964.

23. BALDWIN, R. Some Tentative Calculations of Flame-Merging in Mass Fires. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization. Fire Research Note No. 629, 1966.

24. THOMAS, P. H. The Size of Flames from Natural Fires. Ninth Symposium (International) on Combustion. Cornell, U.S.A., 1962.

25. Home Office. Ministry of Home Security, C. D. Research Committee, Sub-Committee F, Paper No. RC(F) 3a/5. (Restricted).

26. Home Office. Ministry of Home Security, C. D. Research Committee, Sub-Committee F, Paper No. RC(F) Pan 3a/13. (Restricted).

27. BOND, H. Defense Against Fire Effects of Atomic Bombs. Bull. Atom. Scient., 1951, 7, (11) (Nov), 337-40, 352.

28. BRUNSWIG, H. Deployment Experiences of the Fire Protection Services, Vol. III. Hamburg, Germany, 1959. (Uncirculated Report).

29. HESELDEN, A.J.M. Fully developed fires in a single compartment. Part 1, Apparatus and Measurement Methods for Experiments with Town Gas Fuel. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization, Fire Research Note No. 555, 1964.

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