A MULTI-STORY FIRE IN HIGH-RISE APARTMENT BUILDING DEVELOPED THROUGH BALCONIES — INVESTIGATION AND EXPERIMENTS —

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ABSTRACT

Summary of experiments for the investigation of a fire which caused an upward fire spread for over 12 floors through balconies in a high-rise apartment complex is reported. The experiments include indoor tests to obtain fire properties of vertical PMMA fences and outdoor ones with a full scale model of the balcony. The test results suggest significance of the increase of total flame height by the merging of flames and a cooperative effect of the burning of the PMMA fence and combustibles on the balconies for the generation of a tall flame enough to cause ignition on the upper floors.

INTRODUCTION

A fire which started in an apartment unit on the 9th floor of a 20 story apartment complex in Hiroshima-City in the afternoon, 28th October 1996, developed to the 20th floor through the balconies in 30 minutes and resulted in the total burning of 16 apartment units and partial fire damage to 11 apartment units. Figure 1 is a picture taken during the fire and Figure 2 is a summary of the fire damage. The weather was cloudy and there was approximately 1m/s weak wind from northeast during the fire. Almost all process of the floor-to-floor growth of the fire was recorded with video accidentally by a resident, and is summarized in Figure 3. Although the fire growth from the 9th floor to the 12th floor was rather slow, the vertical fire spread on the 13th floor and higher was surprisingly fast; it took only 20 - 30 seconds for the fire to proceed by one floor.

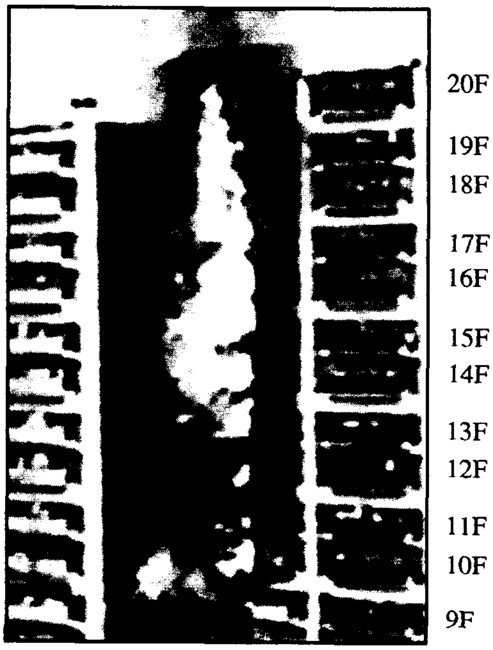


Figure 1 Picture Record of the Fire

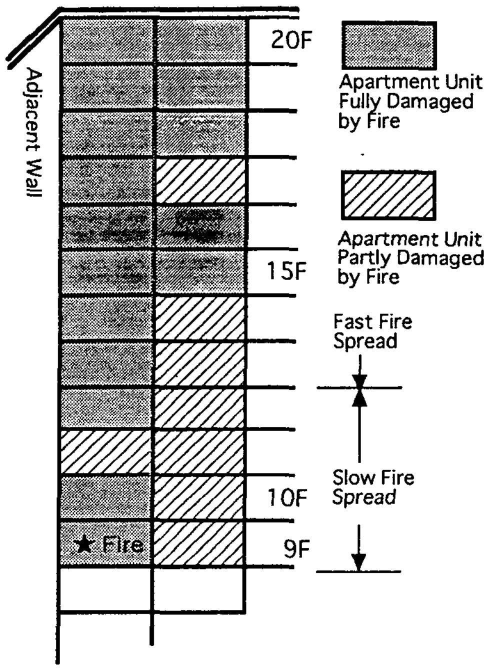


Figure 2 Fire Damage Summary(Interior)

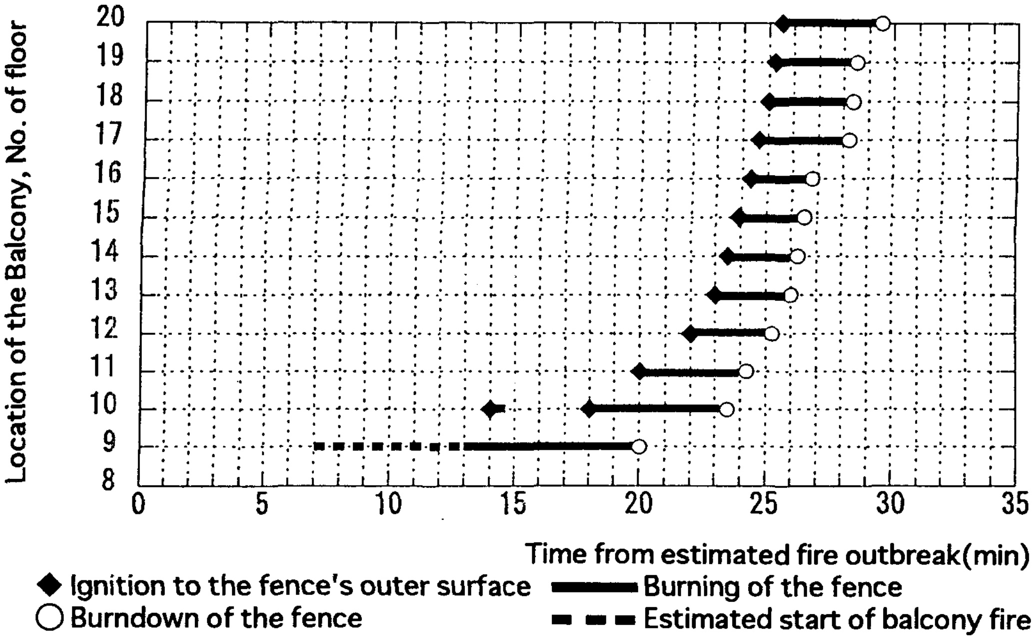


Figure 3 Summary of the Vertical Fire Growth through Balconies

During this fast fire growth, no significant fire was observed in the rooms on the 12th floor and higher, which implies that the combustibles on the balconies were the principal source of the fuel to maintain the fast vertical fire spread. It was the first significant multistory fire in high rise buildings in Japan, and the extremely fast vertical fire spread drew strong interest by fire experts. The Ministry of Construction organized an investigation committee on this fire, and Building Research Institute conducted large scale experiments as a part of its activity[1 - 3]. This report conveys summary of the main results of the investigation and the experiments.

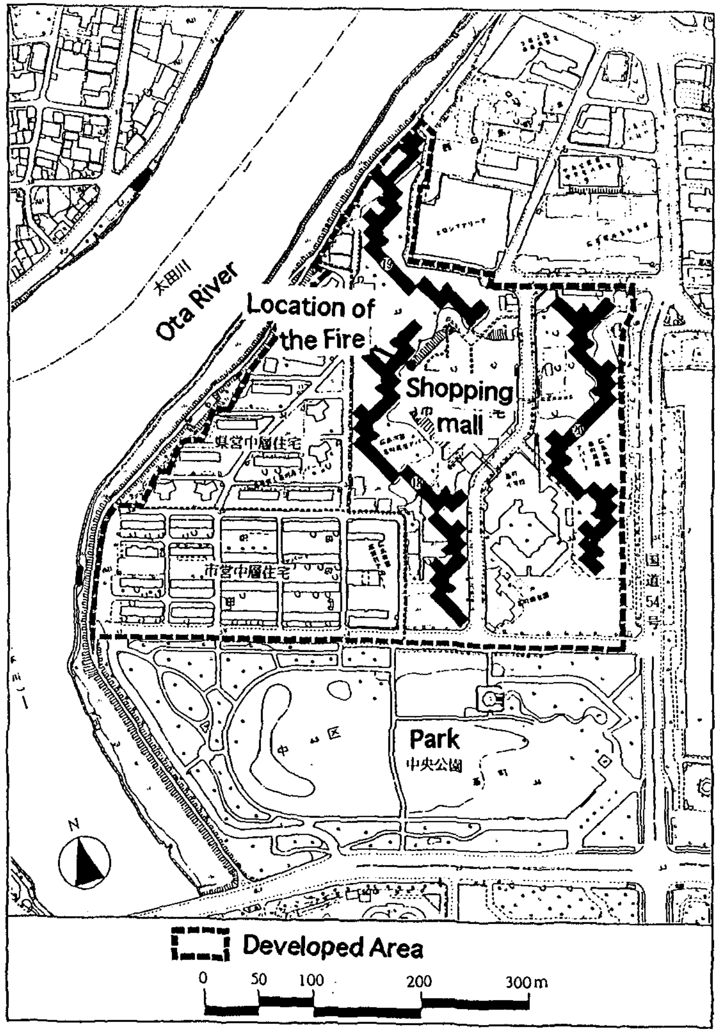
THE BUILDING

The apartment building was built in 1972 for generally low-income families with steel-reinforced concrete frame structure and is owned and operated by Hiroshima-City. The complex consists of 2,964 dwellings in total and has a rather complicated plan as seen in Figure 4. The shopping mall between the building and the road inside the developed area prevented direct approach of fire engines to the burning facade. The building has open-air corridors on every other floor, and the apartments on a floor without such corridor are accessible through a stairway down to the corridor; the general plan and the section of the apartments are shown in Figure 5.

Floor area of each apartment unit is $36m^2$ - $42m^2$. The vertical and horizontal fire separations are reinforced concrete slabs and walls of either concrete blocks or reinforced concrete respectively. The balcony-side external wall of each apartment unit consists of concrete load bearing frames and normal and wired glass windows; there is no solid wall with concrete or metal. The 1.6m deep balcony had a 1 meter tall 8 - 20 mm thick polymetacrylic (PMMA) fence. The fence was supported by a steel frame around the skirt of the balcony, and there was 35mm gap between the fence and the skirt of the balcony floor. Partly for the tightness of the size of the apartment unit and partly because the most of the residents are aged and have continued to live over 20 years, fire load density in the apartment units was generally high; this circumstance generally resulted in notable amount of live load, generally combustibles, left on the balconies. The features of the design and construction of this building are believed to weaken the performance for the prevention of fire spread through the facade. Three fires had already caused fire penetration to apartments on upper floors before the 1996 fire through different routes of the external wall at this complex.

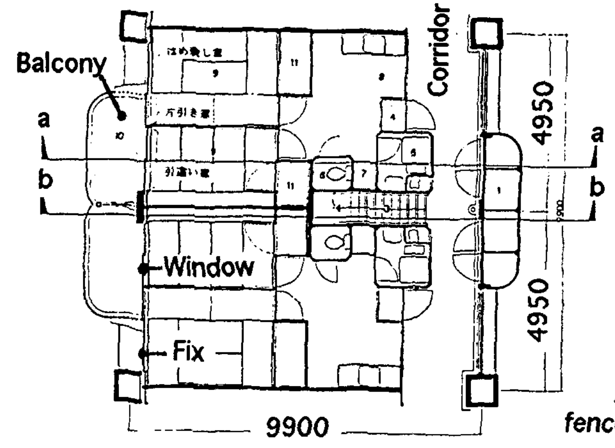
ESTIMATED CAUSES AND MECHANISMS FOR THE FAST FIRE SPREAD

According to the video record of the fire, the PMMA fences were ignited directly by the external

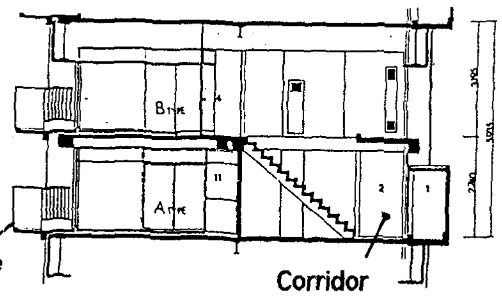


Solid part represents high-rise buildings.

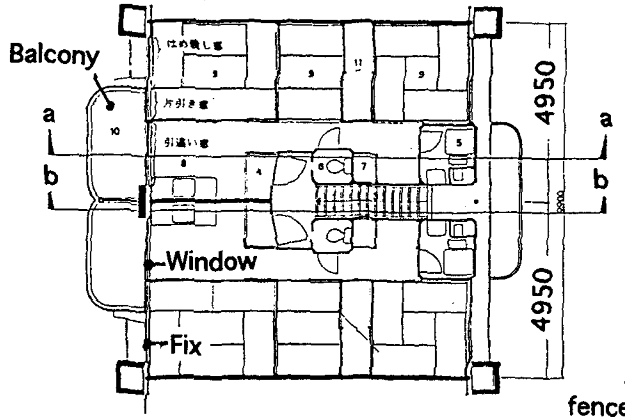
Figure 4 Layout of the Hiroshima Motomachi Apartment Complex



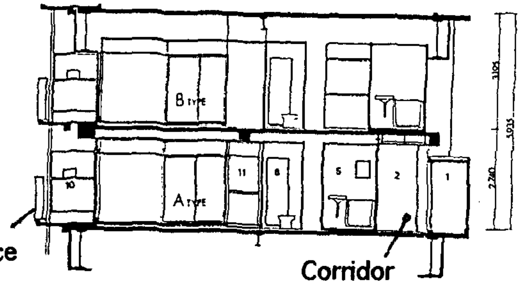
Dwelling Plan
(for "even number"th floor)



b-b section
(stair and public space)



Dwelling Plan
(for "odd number"th floor)



a-a section
(apartments)

Figure 5 Apartment Units of the Hiroshima Motomachi Apartment Complex flame developing from the lower floors during the fast flame spread. It means that the time for fire spread from floor to floor, 20 - 30 seconds, should be equivalent with the time to ignition of the fence material exposed to the external flame. According to the ignitability tests data, the time to ignition of PMMA becomes 30 seconds or shorter only if the level of the external heat flux becomes $50kW/m^2$ or higher. Previous wall flame heat transfer correlations on relatively large fires suggest correspondence of this rather high heat flux with the exposure to an intermittent flame from a 10^{-1} - 10^0 MW fire[4]; frequent attack of the fences by intermittent flames were observed in the video tape during the fast fire spread. Repeated generation of such flame tall enough to cover the fence of the upper floor is believed as the main mechanism to maintain the fast flame spread. This suggests importance of the mechanism generating such a tall flame along the balconies.

PMMA is a very common laboratory material for surface burning. According to the knowledge on its combustibility it was anticipated that the burning of a single vertical surface of a 1m tall PMMA can generate around 2m tall flame, which is not enough at all to reach the upper floor. On a few balconies there were certainly considerable amount of combustibles which may be enough to generate an enough tall flame. The video record actually shows a very tall flame developing from inside the fence of the 16th floor. however, large combustibles on only a few floors should not be an enough explanation for the thorough process of the fast fire spread for over 8 floors.

Several possible causes and mechanisms stood for the surprisingly fast vertical fire spread through the balconies. These include:

1)relative location of the fire to the whole building
2)simultaneous two-face burning of the polymetacrylic(PMMA) fence
3)simultaneous burning of the fence and combustible objects on balconies

Regarding the first possibility, it is widely known that a diffusion flame in fire becomes approximately 30 - 50 % taller in a corner than in an unconfined space due to the restriction of the air entrainment[5]. Also, radiative interaction between the walls around the corner is believed to increase the surface heat flux and accelerate a fire spread in a corner configuration. Although this well known principle was naturally recalled as it was in the corner of the building that the vertical fire spread took place, the fire growing along the balcony seldom flew into the corner during the fast fire spread. It was finally concluded that this mechanism never played an important role in the fast fire spread although it may have had significant influence during the fire spread over the first 2 or 3 floors, which was however rather slow.

If the two surfaces of a vertical combustible slab burns simultaneously, heat release rate is believed to become twice, which should increase the flame height by around 60%[6]. If a single surface burning of PMMA produces a 2m tall flame, its two-face simultaneous burning may produce 3.2m tall flame, enough tall to reach the upper floor. Even if the heat release from the combustibles on any balcony is not enough to reach the upper floor, any combustible object with heat release rate comparable with the single surface burning of PMMA may produce an enough tall flame if it burns with the fence. Within this context, it is still important to clarify what mechanism leads to the both-face burning of PMMA or to the simultaneous burning of the fence and the combustibles. The gap between the fence and the balcony slab was considered as a possible route for the penetration of a flame developing outside the fence into the inner part of the balcony.

However, from various evidence, it was thought that neither of the both surface PMMA burning nor the simultaneous burning of the fence and some combustibles might yet be enough to support a tall flame enough to cover the whole surface of the 1m fence of the upper floor. The concept of an "accumulation of excess flames from multiple burning balconies" was introduced to explain the thorough process of the fast upward fire spread. With the entrainment and mixing as the principal elementary process controlling the flame height, it can be anticipated that, once the height of the flame from each burning balcony exceeds the floor-to-floor interval distance, flames from different floors merge into a very tall flame whose flame height is controlled by the total heat release rate. Preheating of the PMMA fence and the combustibles by the fire plume from the lower floors was anticipated as another mechanism which may have supported the acceleration of the fast flame spread.

THE EXPERIMENTS

Two series of relatively large scale tests were conducted to verify the estimated mechanisms.

The first series(Figure 6) were conducted indoors with 1m tall, 1m wide and 10mm thick PMMA

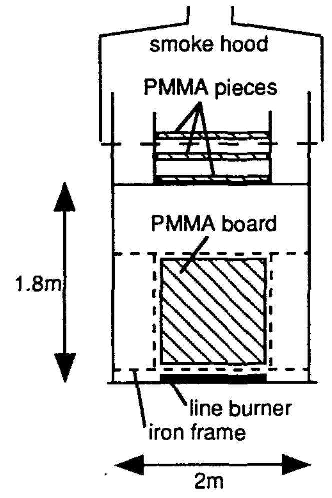


Figure 6 Experimental Setup(Indoor)

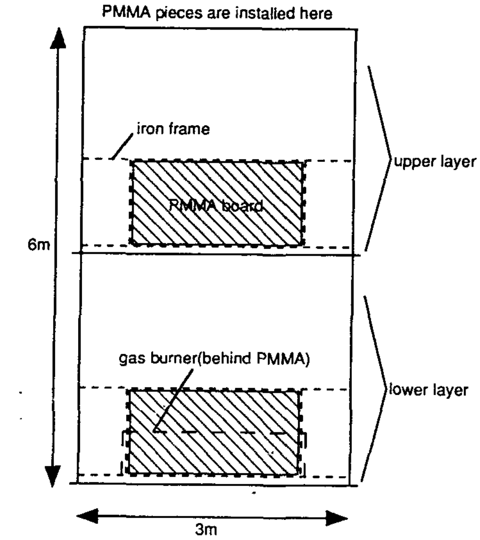


Figure 7 Experimental Setup(Outdoor)

slabs. The specimen was supported with a steel frame and was confined with cement board at the lateral edges to maintain a two-dimensional fire. The main purpose was to look closer the influence of ignition condition and preheating to the burning behavior of the fence. Heat release rate was measured by the oxygen consumption method.

The second series were then conducted outdoors using a full-scale rig reproducing two floors of the balconies(Figure 7). PMMA vertical slabs were installed not only on the two levels of balconies but also on the roof to see the fire spread to the third level. In most of the tests, such untreated combustibles as foamed plastics, fabric and mattresses were arranged on the upper balcony. Untreated acrylic curtain was hung at the location of the glass window. Flames from lower floors were simulated with a 2m square porous propane burner. Its heat release rate was controlled during each test within the range of approximately 1MW - 4MW to reproduce different mode of fires from a flame projection from a single enclosure to a merged large flame. The 35mm gap between the fence and the balcony slab was reproduced in the test rig. Heat fluxes near the fence and at the location of the glass window were measured with Schmidt-Boelter gages on the upper floor. Cabled video camera were installed on the upper balcony to monitor the fire spread on the balcony. Heat release measurement was not conducted for the limitation of the facility. The weather during the tests was relatively mild, and there was 1 - 3 m/s wind from north, from the back of the test rig.

Measurement of heat release rate of the PMMA actually used for the fence of the building for over 20 years was made at $50kW/m^2$ radiation level with the ISO5660 Cone Calorimeter, and its result was compared with the data on a new PMMA slab. Between the new and "used" PMMAs, there was less than 2% difference in the peak heat release rate and in the average heat of combustion and 6% difference in the time to ignition. It suggests that there was virtually no weathering effect on the material we studied.

Indoor tests

Five tests were conducted. The results are summarized in Table 1.There was no sign that single surface burning of a 1m tall PMMA fence make a flame taller than one story. At the test No.1, the single surface burning was sustained until the very end of the test, while at all of other tests the both surface had started to burn before the peak heat release rate was achieved. The time to ignition and to the peak of heat release rate were rather long probably because of the external heat flux from the ignition burner lower than that at the real fire. The time to ignition and to the heat release rate peak at the test No.5 was roughly 40% shorter than that at the test No.5; it is consistent with anticipation from the power proportionality of time to ignition and concurrent flame spread on the temperature difference between the ignition temperature and the ambient. It is important to note that it takes rather long time for the peak of the burning to appear. Although the both surfaces finally burnt and flames higher than 3m were observed at the tests No.2 - 5, there was not any sign that flame

Table 1 Summary of the Indoor Tests

No	Test condition	Time to the peak of heat release rate	Maximum heat release rate (inclusive of ignition source)	Maximum flame height
1	Ignition at the lower edge of one surface with 15 litters/min Propane*	22.0min	700kW	2.0 - 2.4 m
2	Ignition at the lower edge of both surfaces with 30 litters/min Propane	9.3min	1,260kW	2.5 - 3.0 m
3	Ignition at the downward surface with 15 litters/min Propane**	11.6min	1,270kW	
4	Ignition by a large flame covering one whole surface with 150 litters/min Propane	5.2min	1,800kW	3.5 m
5	Ignition after the surface preheating to 150C at the lower edge of the one surface with 15 litters/min Propane	11.7min	1,370kW	

* 15 litter/min of Propane is equivalent with 23 kW assuming the complete combustion.

** The PMMA slab for other tests were supported with a steel frame along each of the four sides of the specimen. For the test No.3, a frame without the lower horizontal bar supported the specimen. The lower edge of the PMMA slab was exposed to the ignition flame at this test. It was to simulate a part of the actual fence not supported from downward with any frame.

height reach the level of the top of the fence on the upper floor(approx 4m) . It means that a single burning of two surfaces of a PMMA fence should not be enough to cover the PMMA fence of the upper floor, and suggests the importance of the "merging effect" of the flames from the balconies. The heat release rate at the test No.4 notably higher than the others may result from the external heat flux enhancement to the burning surface by the large ignition flame.

Outdoor tests

Seven tests including preparatory ones were conducted. Some arrangements were made on the test rig to reduce the wind effects on the flame projection. At all these tests, it was observed that single burning of the PMMA does not cause fire spread to upstairs even if it burns on the both sides. Even a combined burning of the PMMA and combustibles on the balconies did not cause a fire spread to the upper level within the fire load on the balcony used at this test series. The PMMA slab above the roof was ignited only when the 2m burner was fed enough fuel to produce a flame reaching the top of the fence of the upper level. Observations on such conditions can be summarized as follows.

(1)Penetration of the gap

No penetration of the gap between the fence and the balcony slab by flame was observed. It is rational as a flame developing outside the fence should make a negative pressure on the outer side of the fence to its inner side. If it is the mechanism preventing the penetration, any strong wind against the fence might resolve the negative pressure and cause a penetration.

(2)Merging effect

Combined burning of the fence and the combustibles produced only a flame weakly touching the fence on the upper level, but was still not able to ignite it. Combination of a burner flame enough to cover the fence and the burning of the fence and the combustibles produced a tall flame enough to ignite quickly the fence above the roof. This demonstrates the significance of the merging effect in facade fires.

(3)Fire spread from the outer surface to the inner surface of the fence

Once the burner on the lower level was fed enough fuel to cover the whole fence surface and the outer surface of the fence started to burn, clothing and other combustible objects on the balcony was ignited very quickly. The flame above the combustibles then flew to the inner surface of the fence, and ignited it. The combustibles on the balcony are thus believed to play an important role as a "mediator" for the development of fire from the outer surface of PMMA to its inner surface even if the heat release from them is not pronounced.

(4)Penetration of the glass window by fire

According to the heat flux measurement, notable heat flux exceeding the 20kW/m^2 was observed at the location of the window only when either the combustibles on the balcony were burning or a part of the flame outside the fence hit the balcony ceiling and flew horizontally beneath the ceiling toward the window. Sustained ignition of the curtain occurred only after such events. This suggests that fire penetration of a window fast enough to prevent effective fire fighting should take place only when the external flame becomes higher than the balcony ceiling or notable amount of combustibles on the balcony starts to burn, although weaker radiation may also result in slower penetration of glass window by fire. This may partly explain the weak damage to the interior in the 11th floor where the fire load on the balcony was small.

CONCLUSIONS

The estimated controlling mechanism for the vertical fire spread through balconies can finally be summarized as shown in Figure 8. The discrete arrangement of vertical PMMA along the balcony and combustibles behind the fence are believed to have augmented the total heat release through simultaneous burning of the both sides of the fence and the combustibles, though many laboratory tests dealing with pure surface burning suggest that such discrete arrangement generally delay or prevent flame spread. The significance of the merging effect implies imoportance of fire protection strategy to limit a fire to first one or two stories in highrise buildings.

Hiroshima City decided to replace the PMMA fence with noncombustible ones after this study. This is believed to reduce significantly the risk of floor-to-floor fire spread in this complex.

ACKNOWLEDGMENTS

For more details of the analysis, references[1 -3] should be consulted with. The authors wish to acknowledge the partial support for the tests and the cooperation in the site investigation by Hiroshima City. The authors acknowledge especially the efforts of Messrs. T.Nakaoka, Y.Tamura and other fire fighting team of Hiroshima City throughout the investigation and the experiments.

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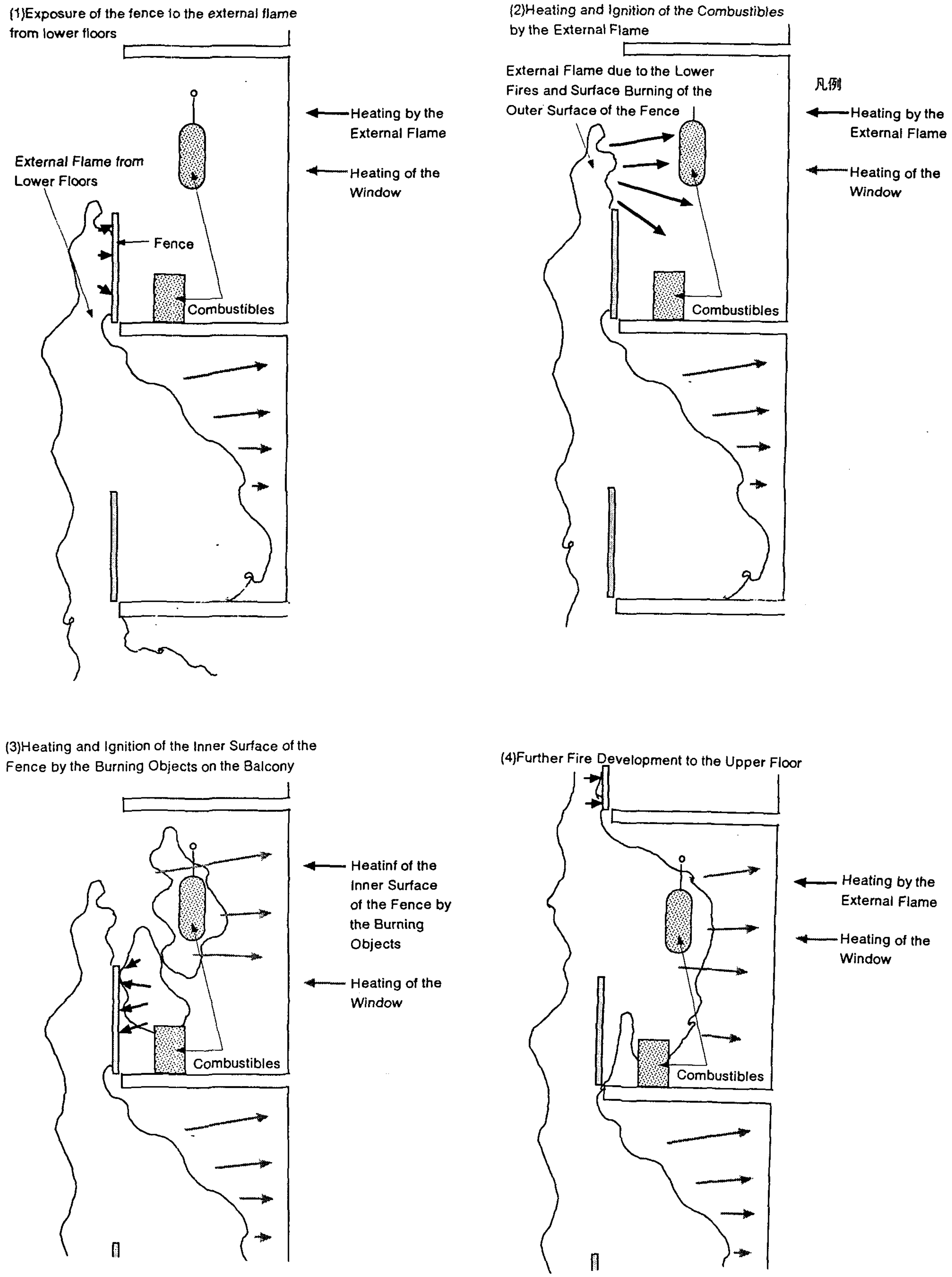

Figure 8 Estimated Controlling Mechanism for the Vertical Fire Spread through Balconies