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High-Rise Buildings with Combustible Exterior Wall Assemblies: Effect of Number of cavity fire barriers on Upward Flame Spread.

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ABSTRACT*: This paper aims at studying the effect of the number of barriers when a fire outbreak in high-rise buildings through the cavity between the external wall and the Aluminium Composite Panels ACPs cladding system. A model for ACPs is presented by addressing the main parameters as the following: - The thickness and the number of fire barriers between the facade wall and the cladded material ACPs, and the methods of installing these barriers.*

To verify the proposed model numerical simulation analysis was performed using Grasshopper and Galapagos software. Where Galapagos is an Evolutionary Algorithm EA-oriented tool. The new integrated model of the ACPs suggested changes in the materials used as well, such as wet and hot insulation using the latest special products such as Fenomastic sanitary emulsion paint.

The input parameters to the EA are; the Initial fire temperature, facade material elements, facade elements' properties, elements' fire resistance, and time.

The simulation test results show that using four barriers in the air cavity plays a major role in neutralizing and limiting spread to the external facades, minimizing the risk, and reducing harmful effects to the inhabitants in the high-rise buildings.

KEYWORDS*: Aluminium Composite Panels ACPs, High-rise buildings, fire barriers, air gap, Galapagos.*

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I.INTRODUCTION

The importance of this research stems from frequent fires in tall buildings, which are still spreading worldwide, specifically the phenomenon of a vertical fire flame mass. Only a few researchers have studied this phenomenon with great importance.

However, there are no fundamental solutions to this problem, and the danger still exists and threatens all residents of high-rise buildings Although the use of all modern tools and means reached by the latest scientific research, there is still a danger that exists today from the outbreak of vertical fire flames in high-rise towers from the cavity between the external wall and the ACP cladding system. Meanwhile, the damages resulting from these fires are large and costly, whether human, psychological, or material, the largest example of this topic is the Grenfell Tower in the United Kingdom in 2017, which resulted in the death of more than 70 residents and the displacement of all residents of the tower in addition to its complete burning and damage.

The danger of vertical fire flames that have appeared recently in metropolitan cities around the world is well known to experts, researchers, and those interested in the security and safety of residents in high-rise buildings. Moreover, the unique advantages and characteristics of ACPs made them the first choice for architects and engineers working in architectural design, and the construction sector in general. After using these panels for cladding extensively, especially in high towers, in a contemporary cities like New York, Tokyo, Dubai …etc. It was found that there are still several disadvantages related to such panels. Such disadvantages result from the use of flammable materials in its components and the presence of an air cavity that helps in the spread of vertical fire flame and defects in fixing them on the facades.... etc.

A specific focus on the external facade system and ACP insulation is necessary for the UAE material requirements. The nature of fire spread with ACP cladding materials containing combustible core materials raises concern over the safety of building occupants and firefighters [1].

The presence of the air cavity led to the emergence of a serious problem, which assists the rapid spread of vertical fire flames in the event of a fire in the upper floors and apartments.

Some studies appeared recently to solve the problem of air cavities [2-7], and a little bit researchers presented solutions by installing fire barriers and suggested one or two barriers, but the problem still exists, and the number of fires is increasing.

The fire behavior of ventilated cladding systems made of aluminum composite panels ACPs has become a topic of concern, The fire performance of a cladding system comprises not only the cladding panel and the insulant but also air cavities, cavity barriers, and mounting and fastening elements. In a real fire, all these components interact significantly. It was also confirmed that the Grenfell Tower fire in (UK, 2017), where there were installed barriers; however, the installation geometry of the cladding system developed an interconnected network of cladding cavities, allowing the fire to spread rapidly [8].

It was concluded that the use of combustible insulation in exterior wall claddings without proper fire barriers and protection would potentially cause rapid fire to spread and severe fire damage and loss, the horizontal fire barriers using 300 mm high non-combustible insulation were effective to delay the fire spread on exterior walls [9].

The outer cladding may be aluminum composite material ACM, high-pressure laminate HPL, or mineral fiber board. ACM consists of two thin sheets of aluminum (~ 0.5 mm) sandwiching a layer of polymer (usually PE), PE filled with metal hydroxide fire retardant FR, or predominantly non-combustible. NC, as an inorganic composite or metallic filling. FR panels contain around 65% aluminum hydroxide or magnesium hydroxide, having a fire retarding effect through endothermic dehydration and the subsequent release of water, to suppress flaming [10].

This proves that most of the recent external cladding are non-combustible materials, however, many fires around the world are still spreading and increasing with great acceleration, which prompted researchers to observe this phenomenon and research it carefully and deeply, in order to reach positive results and reduce the risk of fires that spread on the external facades of tall buildings and prevent them from spreading as much as possible, especially the vertical flames that appear suddenly and very quickly leading to severe damage in population, materials, and buildings themselves.

Fire stopping (fire barriers) is required for all interior gaps at fire compartment boundaries. This includes gaps between slabs and exterior wall systems such as curtain walls. The fire stopping must have a fire-resistance rating equivalent to that required for the fire compartment boundary [4].

White stated that the panels are typically fastened to the steel battens by either of the following two methods. Flat stick method - flat cut ACP panels adhered to steel battens using double-sided adhesive tape. Cassette mount method - the edges of the panels are folded at right angles and are rivet or screw fixed to aluminum or steel channels or clips which are in turn screw fastened to the exterior wall [11].

Mineral wool fire stops barriers (at least 50 mm thick) are required for buildings of three or more stories fitted with combustible external insulation. The fire stop barriers must be installed to the cladding at intervals of not more than two stories.

Regarding the flame heights the experimental setup allowed containing the entire flame between the walls—no flames were emerging outside along the sides or above the walls. With cavity widths of 0.04 m and greater the flames did not fill the entire cavity width. As the cavity width was reduced the plume flow appeared to be more vertically oriented and the flames filled the entire cavity width. The transition to the mode where the flames filled the entire cavity width was observed to occur at the cavity width of 0.03m and 0.04 in the experimental tests. The visual observations clearly indicated that the flame heights increased with reduced width [8].

White stated also that ACP is typically installed to exterior walls on steel channels or battens/top hats. This can create an air cavity (typically about 40 mm) between the next surface within the external wall cavity (typically sarking or other weather resistive barrier) and the cladding [11].

When the fire inside the cabin develops to be in its most severe stage, flames may escape from the openings, forming outer flames, also known as Interface fires. Structural parapets (e.g., balconies, eaves, and overhangs) greatly influence the vertical spread of the opening spill column. Numerical investigations show this chamber fire and prevailing ventilation conditions. Strongly influences indoor fire behavior through oxygen availability. And the development of the flame emanating from the outside because of natural factors such as wind and high temperature [12-15]

"It is found that the characteristics of External Venting Fire strongly depend on opening dimensions and for large opening widths EVF tend to emerge from the opening as two separate fires." [16]

"As observed in real high-rise building fire incidents, flames can eject from many windows over multiple floors and the interactions between multiple fire plumes are very complex. This needs to be studied further and more deeply: the ejected flame interaction of multiple windows with different arrangements and wind conditions are suggested to be further taken into consideration." [17]

Although there has been significant progress in understanding the window-ejected fire plume behavior from a compartment with external wind conditions recently, there are important remaining aspects to be addressed, such as the wind direction is variable, leading to different degrees of impact on window-ejected fire plumes, forming complicated facade boundary conditions. There has been little research on the ejected fire plume characteristic parameters (heat flux by radiation and convection; temperature profiles; and flame dimensions) for the facing and sideward wind conditions. These are not only determined by the flame (hot buoyancy): the wind-cooling effect should be considered. All these aspects should be carefully studied in the future [17,18,19].

The conducted experiment it was found that the results indicate that, without a barrier, fire starting at the middle of the wall generated a higher peak. The heat release rate HRR than that starting at the bottom, which was, in turn, higher than that starting at the top. When the insulation panel below the barrier was 1 m high, the upward fire spread from the bottom could be stopped by 40 cm, but not 30 cm, barriers. However, when the insulation panel below the barrier was 2 m high, even the 40-cm barriers failed. Lastly, the downward fire spread from above could not be stopped by a 40-cm barrier due to the dripping of burning plastics. The study highlights the limitations of horizontal fire barriers in preventing vertical fire spread over exposed B2-grade polystyrene insulation and establishes protocols for further investigations [23].

By reviewing the previous literature and many others, it has become clear that the use of fire barriers in air cavities is effective and gives positive results, but it is not sufficient to prevent the spread of fires in general and the spread of vertical flames in particular, and based on all of the above, the researchers here have enumerated this study, where they conducted a simulation to test a new proposed model based on the theory EA and using the application.

In this work, a novel model for ACPs is developed and investigated to minimize the fire risk in a high-rise building. A varying number of fire barriers, accompanied by various dimensions of the air gap, were used. To get the optimum gap space and the economical number of fire barriers, an evolutionary algorithm EA was proposed and performed using Rhinoceros, Grasshopper, and Galapagos, [20].

II.THE CONSTRUCTION OF THE ACP NOVEL MODEL

The novel model proposed was designed, prepared, constructed, and tested as per shown in "Fig.1". This numerical simulation resembles the experimental worldwide tests which aim to examine, improve, and develop the exterior wall assemblies that are cladded by ACP's material system, in compliance with applications and laboratory tests approved globally as BS8414 part 1 & 2, ISO 13785 part 1 & 2, NFPA 285, SP105, CAN/ULCS134, DIN 4102-20. The proposed tested model "Fig.1" is Constructed as the followings:
2.1 From the main metal skeleton size 5453mm in length (height) and 4551mm in width.
2.2 The fire opening at the bottom of the model size 75.7cm in length (height) and198cm width.2.3cm. Proposed model layers as the following:
2.3.1 200 mm block wall.
2.3.2 15x15x1mm aluminum U channel [panel joint sealing].
2.3.3 50 mm mineral wool insulation density 24 kg/ m3.
2.3.4 The optimal gap (cavity) thickness is 111mm.
2.3.5 4mm aluminum composite panels.
2.3.6 Fenomastic hygiene emulsion silk paint.
2.3.7 1.5 mm thick galvanized steel [ASTM a653 / a653m] window flashing, [21].

The novel model contains all the materials and elements that were tested by conducting the simulation test for the experiment. Such a model succeeded in passing all stages of the experiment, which gave promising results in reducing the spread of fire and flames from one floor to another. The following practical methods may help in resisting and controlling the propagation of external fire and vertical flames [22]:
- Strangulation: where the fire is strangulated by preventing Oxygen.

- Isolation: where all flammable materials surrounding the fire were eliminated.
- Starvation: where the fire is killed due to the lack of materials to be burned.
- Break chain reaction: where the fire-positive agents were isolated from the fire surroundings; firefighting and control.

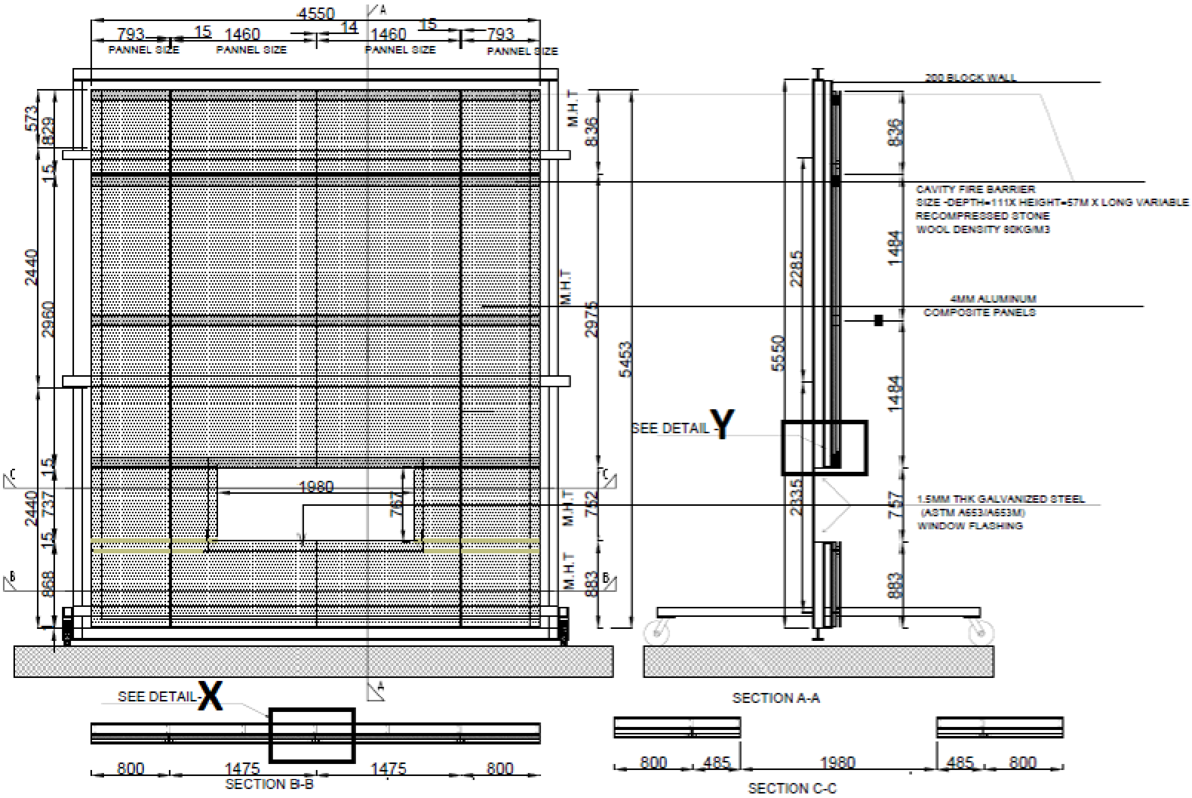


Figure 1 (a): Exterior wall assembly model.

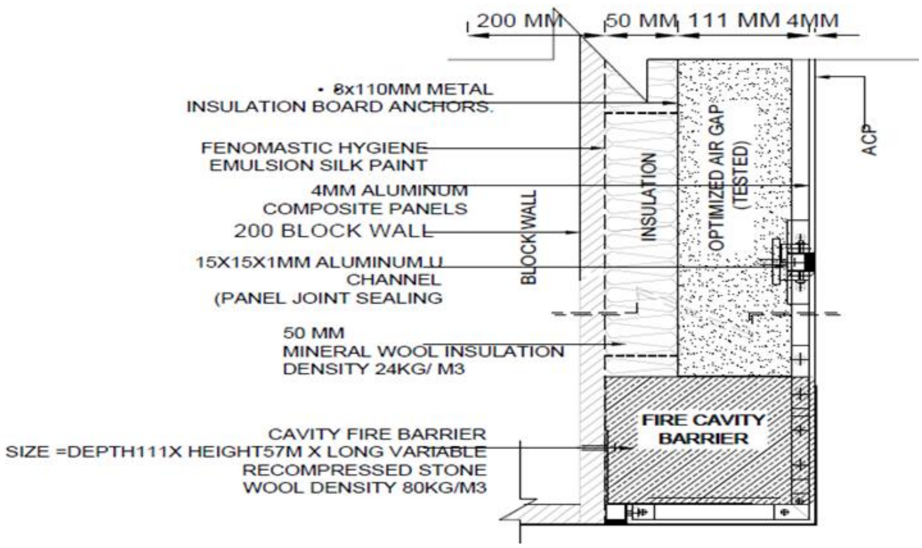


Figure 1 (b): Details of sections Y - Y.

Figure 1: Details of the proposed tested model of ACPs [21].

III.THE SIMULATION RESULTS AND DISCUSSION

It was found that one of the main factors for the spread of vertical flames in skyscrapers is the presence of gaps or cavities in most models used until today.

The air gap between the Aluminum Composite Panels ACPs and the external wall is a major factor in fire extension on the facade of high-rise buildings, it is playing a very important role to prevent vertical fire flame spread, more than one problem was found in this position, the first being depth of the cavity [21]. The horizontal fire barriers using 300 mm high non-combustible insulation were effective to delay the fire spread on exterior walls [9]. The air gap is also considered as a leveling monitor to adjust the defects in the civil works in the external walls.

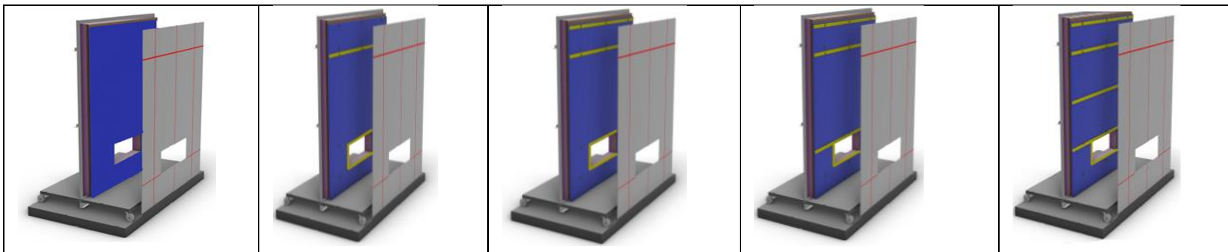
"Fig.2" presents the size of air (cavity gap) between the wall and ACP which is more than 300 mm [11].

Figure 2: Cassette mount installation of ACP onto the wall (photo by CSIRO) [11].

As the result of the simulation test, the output for the air gap from Evolutionary Algorithms EA is = 11.1cm which holds the most precise values for the equation to reach the targeted fitness point with delta time dt = 2416 sec (~40.27 min), that will lead to the great benefits and starting economical products in the industrial construction field for validation of the novel model of ACP [21].

Five consecutive simulation tests were performed, and each test takes about 45 minutes. The first one is performed assuming no barriers. The next four were performed adding one barrier each time. In addition to the fire barriers that are located and installed all around the openings such as doors or windows "Fig.3".

The barriers proposed were sufficient and effective in suffocating, seizing, and controlling the spreading of the vertical fire flame.



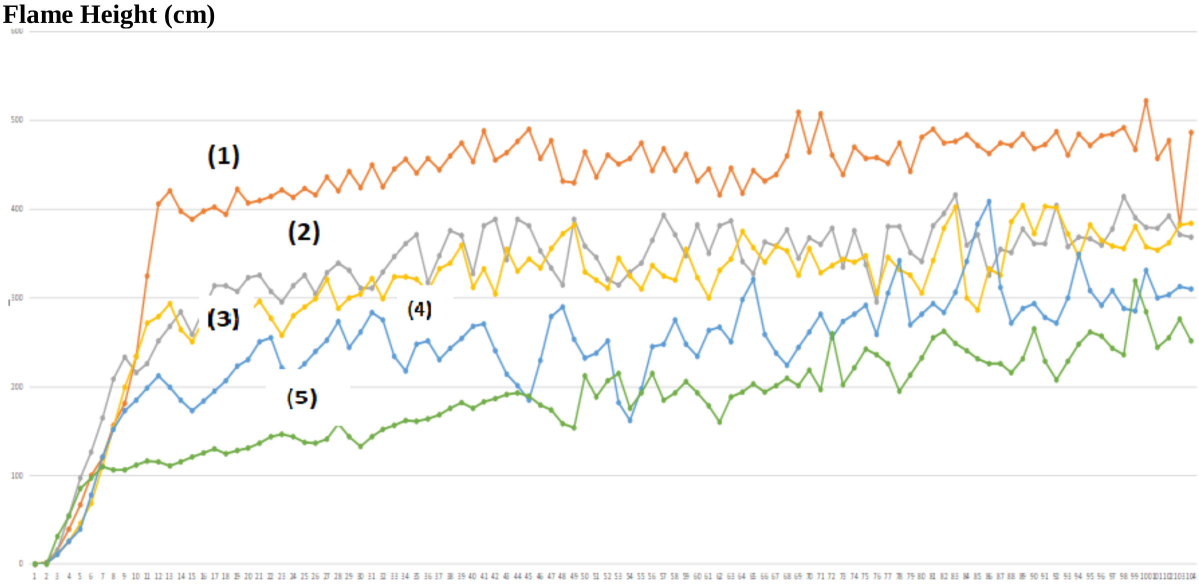
1.No fire-barriers	2. One fire-barrier	3. Two fire-barriers	4. Three fire barriers	5. Four fire-barriers

Figure 3: Positions of fire barriers throughout the simulation test.

Adding new barriers will suppress flame propagation, but it is not recommended to use a great number of barriers because of economic and technical purposes.

"Fig.4" shows the flame height versus time for the fire cases shown in "Fig.3" where the number of cavity barriers changed.
With no barriers, as shown in line diagram number (1), results indicate the highest level of the fire flame, which reaches the five-meter and a little bit more, that's of no barriers.
With one fire barrier as shown in line diagram number (2), results indicate that it is 1.00 m lower than no using any barrier.
When using 2- barriers as shown in line diagram number (3) present a small difference, in the height of the flame lower than when using one barrier.
Using 3 barriers, as shown in line diagram No. (4), it was found that the height of the fire did not exceed 2.50 m.
When using 4 barriers, as shown in line diagram No. (5), a significant decrease in flame height and control of the fire, in general, was observed.
Therefore, this proves that the use of 4 fire barriers is sufficient to reduce the risk of fire spreading, isolating, and suffocating in general and neutralizing the risk of vertical fire flame.
For practical and economical purposes, it is not recommended to use more than 4 barriers at this distance.

Flame Height (cm)



Time (min)

1.No Cavity Barrier, 2.1-Barrier used, 3. 2-Barrier used, 4. 3-Barrier used, 5. 4-Barrier used

Figure 4: Flame heights versus time with various numbers of cavity barriers.

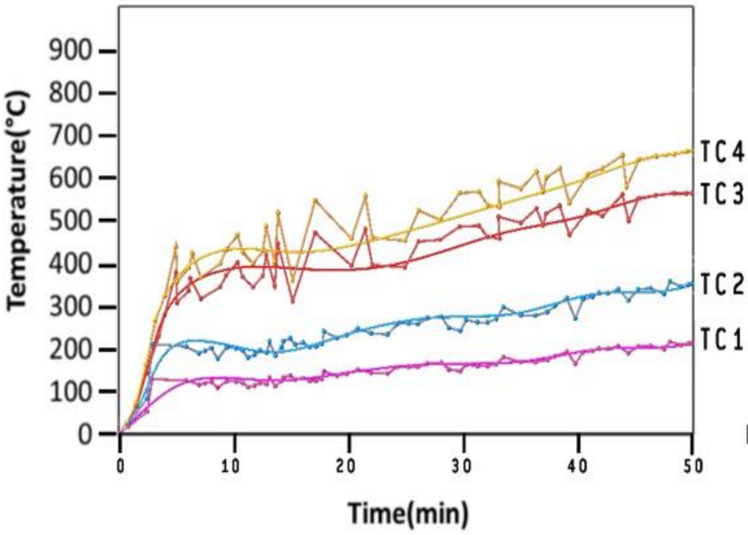


Figure 5 (a). Shows the temperature variation, with time recorded at each thermos couple TC.

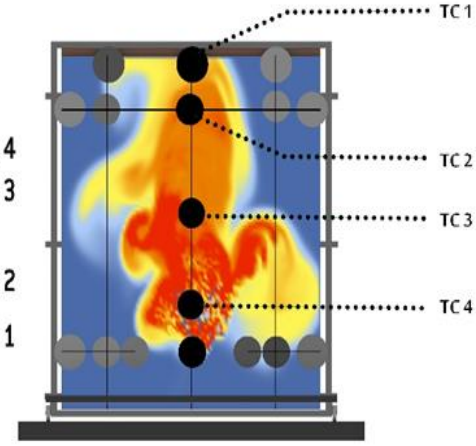


Figure 5 (b). Shows the positions of the adjusted form Thermocouples (TC1,2,3,4) where the flame temperature is recorded

It is clear from "Fig.5", that (TC1) recorded the lowest temperature, it raises within 5 minutes up to 140 ℃, and very slowly developed to a maximum of 190 ℃ within 50 minutes.
(TC2) records show that the temperature raises up to 220 ℃ within 5 min. similar to TC1, but it gradually developed up to 300 ℃ within 50 minutes.
The record of (TC3) shows an overshoot of up to 370 ℃ within 5 minutes. In the next 50 minutes, the temperature was raised up to approximately 500 ℃.
The data presented in "Fig.5" are recorded in the existence of 4-fire barriers. This gives additional proof of the importance of such a barrier.
In conclusion, “TABLE 1" presents a comparison between the proposed and tested novel model and the traditional model (classical).

Table 1: The Table Shows the New Main Hypothesis Compared with the (Traditional) ACP System.

Serial No.	Design Parameters of ACPs	Traditional Model	Proposed and Tested Novel Model
1.	ACPs itself combustible with polyurethane core	- Old traditional model	
2.	ACPs are noncombustible with a mineral core A2	- The latest product of ACPs A2	ACPs noncombustible mineral core A2
3.	Waterproofing system	- Classic Bitumen Paint	Fenomastic hygiene emulsion silk paint.
4.	Heat insulation system	1. Rock wool 2. Polystyrene foam	Mineral wool.
5.	The gap between the wall and ACPs.	The size of the gap allowed up to 300mm.	The optimal gap (cavity) thickness is 111mm.
6.	Joints between Panels.	1. Not closed properly 2. Mastic used is flammable	.Prolastik matt silicone sealant.
7.	(Cavity barriers) Existing horizontal fire-rated barriers (compressed stone wool size up to 300mm *57mm).	One or two barriers are used.	Fire barriers used are 4. (Compressed stone wool size 57mm *111mm).

The items that have been tested and proven the success of the model in detail are: -

1. ACPs non-combustible mineral core A2.
2. Fenomastic hygiene emulsion silk paint.

3. Mineral wool insulation 50mm thickness, density 24kg/m3.
4. Optimal gap (cavity) thickness is 111mm.
5. Prolastik matt silicone sealant. (non-flammable material) should be closed and fixed properly.
6. The Economical number of cavity barriers used is 4. (Compressed stone wool size 57mm *111mm).

IV.CONCLUSIONS

The results of the simulation test for the proposed ACP model, show that a 4 number of cavity barriers are required to be used in external wall assemblies to reduce and control fire spread. Its contribution in reducing the vertical flame is considerable to confine, suffocate, and control the fire and prevent it from spreading.

In addition, it works to discourage and prevent the spread of vertical fire flames that lead to the transmission of fire to the upper floors in tall buildings, which poses a great danger to lives and property.

The results are reasonable and promising and will become a base for further future research.

Furthermore, it will facilitate and assist industrial manufacturers to produce and install safe and secure external wall assemblies.

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