Title: **Solutions for Fire & Life Safety at Extreme Heights**

Author: Simon Lay, Director of Fire Engineering, AECOM

Subject: Fire & Safety

Keywords: Evacuation
Fire Safety
Performance Based Design

Publication Date: 2014

Original Publication: CTBUH 2014 Shanghai Conference Proceedings

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

# Solutions for Fire & Life Safety at Extreme Heights
# 超高层建筑消防与生命安全解决方案

Simon Lay

**Simon Lay**

AECOM
1 New York Street
Manchester
M14HD UK

tel (电话): +44 161 601 1700
email (电子邮箱): simon.lay@aecom.com
www.aecom.com

**Simon Lay** joined AECOM in January 2012 as their Director of Fire Engineering. Simon is an experienced, professional engineer with a grounding in the practicalities of on-site delivery coupled with 20 years of experience in the delivering of specialist design consultancy services. A keen road and off-road cyclist, Simon can often be found cruising along a quiet country road, or throwing himself carelessly down a steep rocky mountainside. Having adopted a bicycle as his main form of transport he gave up owning a car in 2010 as a demonstration of his commitment to sustainable design and living.

Simon 2012年1月加入AECOM并出任消防工程总监一职。作为一名从事设计顾问工作20年，拥有丰富经验的专业工程师，他在项目现场交付方面拥有丰富的经验背景，。他热心于公路和越野自行车运动，在安静的乡村公路或陡峭的岩石山间可以经常看到他的身影。从2010年开始，为了践行对采用可持续发展的设计和生活方式的承诺，他放弃汽车而选择自行车作为主要交通方式。

## Abstract

The world currently only has two "megatall" buildings. However, more are planned and some potential schemes will push beyond "megatall" to "hyper-tall". As construction technology considers such schemes, how can we ensure that they are safe?

This paper will consider:
a. The challenges associated with achieving fire safety in and beyond megatall buildings.
b. Set out solutions based on current technology and mention what would happen if existing building codes were applied to hyper-tall buildings.
c. Discuss areas of emerging technology which could influence future solutions.
d. Make reference to completed projects, schemes currently in design and proposed schemes.

The paper demonstrates that solutions to maintain safety could significantly influence or even restrict future tall building design and construction unless innovative solutions are applied and developed.

**Keywords: Tall Buildings, Fire Safety, Performance Based Design, Fire Engineering, Evacuation, Fire Fighting**

## 摘要

目前世界上仅有两座超越一般超高层的建筑，但是一些方案和设计将要把超高层推向一个新的高度。在这些建筑技术的发展过程中，我们要如何确保其安全?

本文将讨论:
实现超高层及更高建筑高度所面临的建筑消防安全的挑战。
依据现有技术条件的解决方案，并提出依据现有规范设计超高层建筑可能出现的问题。
讨论可能影响解决方案的新兴技术领域。
依据目前设计和所提出的方案中已完成的项目和计划提出参考意见。

本文着重论证只有应用和发展创新性的解决方案，采用原有方案维持安全才不会严重影响甚至限制建筑设计和施工。

**关键词: 高层建筑，消防安全，性能化设计，消防工程，疏散，灭火**

## Introduction

Fire & life safety codes and the resulting building designs have often been reactive. The Great Fire of London led to requirements for fire separation of buildings (Reference 1). Fires like Stardust (Reference 2) led to changes in laws on internal linings. First Interstate Tower (Reference 3) led to a focus on the benefits of sprinklers in high-rise buildings. However, a reactive approach to fire safety is avoidable.

In the wake of the events of 11 Sept. 2001, the conclusions reached by NIST included recommendations (Reference 4) to move away prescriptive requirements and instead proposed that, for tall buildings, a performance based approach should be adopted.

## 前言

消防与生命安全规范的制定以及按其要求进行的设计，通常是通过对事故的总结而进行的。伦敦大火发生后，建筑防火分隔的要求得以提出 (文献1) ; Stardust火灾事故 (文献2) 导致法律对内部衬里相关规定的改变; First Interstate Tower (文献3) 火灾促使人们关注高层建筑使用喷淋系统的有益之处。然而，这种以被动方式实现消防安全的方法是可以避免的。

2011年"911恐怖袭击事件"发生后，美国国家标准与技术研究院在结论 (文献4) 中提出建议: 在高层建筑中，可采用性能化设计方法取代传统处方式设计。

A performance based approach to fire & Life safety can be summarized by the following:

- Identify
  - Who might be at risk.
  - What hazards might generate risk.
- Define solutions
  - Remove hazards
  - Mitigate hazards

The process of identifying who is at risk and what they are at risk from, defines the "performance" being sought. In relation to fire safety performance based design is, in essence "make it safe and prove it is safe". Performance based design can also go beyond just life safety and the performance parameters can be extended to include a wide range of other concerns such as property protection and business continuity.

Performance based design allows engineers to ask; "what if" rather than assume that the "if" of the future is the same as the "what" of the past. Performance based design also frees designers and the approval authorities from having to build fire safety codes purely on disasters of the past and instead allows the safety of future tall buildings to be considered.

This paper considers how performance based design can be used proactively to overcome the challenges arising in buildings at extreme heights such as:

- Will fire fighting operations need to take into account interaction with non-evacuated occupants.
- Can we rely on assuming simple occupant behavior patterns such as instruction compliance?
- Do the traditional ASET vs RSET concepts need reviewing for hyper tall buildings?
- How can we take into account legacy and evolution of buildings over time?
- Should we challenge our preconceptions about what is adequate reliability for fire safety systems?

However before discussing these items, it is important to question what form tall buildings will take in future and how the factors driving the evolution of hyper tall buildings will impact on fire safety.

## The Future of Tall Buildings?

If you ask why tall buildings are built and then consider some of the macro and micro economic changes to our environment, you may well question whether tall buildings are inevitable. You will certainly question what types of tall buildings are going to dominate in future years and as a result you will question how fire safety will be achieved.

Tall buildings were traditionally driven by a single use such as offices, residential or hotels. There may be some retail or leisure uses in a podium and perhaps a viewing deck or restaurant at height but the main driving force behind creating volume at height has mainly been the office, residential or hotel use.

Tall commercial office buildings remain popular, but workplace trends suggest this may not last. The office is not dead; it retains a place in the workspace culture and is likely to do so for some time.

消防和与生命安全性能化设计方法可以概括为:

- 识别
  - 谁可能处于风险之中?
  - 哪些危险源会产生风险?
- 明确解决方案
  - 消除危险
  - 减轻危险

识别面临风险的主体以及风险来源的过程，可以明确所需实现的目标; 关于消防性能化设计，实质上是使建筑设计达到安全水平并证明其安全性。性能化设计目标除了需要实现生命安全外，还可以包括财产保护和防止经营中断等方面。

性能化设计允许工程师做假设性提问，这种假设并非指以往事件再发生会如何。性能化设计可以使设计师和审批部门得到另一个考虑方向，审批部门可以不再纯粹依赖于灾难经验制定规范，而允许考虑未来高层建筑可能面临的安全问题。

本文考虑了如何应用性能化设计的主动方法克服超高层建筑面临的挑战:

- 灭火行动是否需要考虑非疏散人群的影响?
- 仅假设简单人员行为设计模式，如指令式，是否可靠?
- 传统的可用疏散时间ASET和需要的疏散时间RSET的概念在超高层建筑中的沿用是否需要重新验证?
- 随着时间的变化，如何兼顾建筑的传统和发展?
- 是否应该对原消防系统的可靠性提出质疑?

在讨论以上问题之前，更为重要的是考虑超高层建筑未来将会采用何种形式，以及推动超高层建筑变革的因素将如何影响其消防安全。

## 高层建筑的未来?

如果你要问为什么会建高楼大厦，考虑到环境中宏观和微观的经济变化，你还会问兴建高楼大厦是否势在必行。你也一定会问哪种建筑类型会称霸于未来，消防安全将如何实现。

高层建筑过去通常具有单一使用功能，例如办公、住宅或者酒店。建筑中偶尔会有零售和休闲功能区，或者观景台和饭店，但是站在建筑高度的角度，主要驱动力仍是办公、住宅和酒店 。

高层商业办公建筑目前仍然颇受欢迎，但是工作场所的发展趋势表明这种情况可能不会持续很久。办公室并不会消失，并且在一段时间内，它仍将在办公空间文化中保有一席之地。不过，工作人员已经适应了远程办公，要容纳更广泛工作年龄群并满足其不同生命阶段的需求，意味着建造环境友好的、办公高效的工作场所变得越来越难。上下班过程的拥挤占用了工作人员10%至15%的非睡眠时间，既痛苦又无成效，也是不经济的，从可持续发展的角度来考虑显然是不现实的。这一切都将发生改变。

拥有前瞻性的公司开始构思将办公室打造成更像是一个私人俱乐部，提供一个员工交流协作的场所。打个比方来说，未来的办公室更像是散养家禽在储料器旁聚集的场所，而不是在笼子中饲养母鸡的工厂。这意味着将需要数量更多但空间较小的办公室。而公司总部摩天大楼很可能在10年内消失，更多公司将共享同一地址，并且只占据一层而不是一半甚至整栋建筑。

However, workers have adapted to remote working and the need to accommodate a wider range of age groups and worker's life stages means that creating offices that are happy, productive workplaces is becoming increasingly difficult. Commuting congestion robs people of c. 10% - 15% of their waking hours; this is both miserable and unproductive. The notion of creating, a separate space to work rather than exploiting the other sheltered spaces where people could work like home or cafes is uneconomic and when you consider it in terms of sustainability frankly absurd. All this will change.

Forward looking companies are starting to think of the office more like a private club, a place for their staff to meet and collaborate. The future office is more like free-range poultry meeting at food hopper than individual factory farmed hens shoved into tiny cages. This means you need more offices, but less space per office. The corporate skyscraper HQ may well be gone within 10 years and more companies will share the same vertical address, each taking only one floor rather than dominating half or all of the building.

Where possible, existing building stock can be refurbished to meet the new work culture. Central business districts already have good communication links so they can readily act as hubs for the new style of working. However, it is possible that the current group of towers in planning at major cities like London and New York will be the last. Some lag in this process will happen in cities that continue to mature such as some Asian centers in Africa and in S. America, but eventually these locations will reach the same conclusion.

Considering residential buildings, the world population continues to grow, but this growth is slowing. Current predictions (Reference 5) suggest the global population will level out at 9.5 billion, but for some time we expect the population to increase in developing countries and emerging economic zones. There is limited pressure on existing cities to build high-rise homes for the rich; the driving force is typically financial opportunity rather than a physical need. There remains a need for homes for those of lower income. Slums still dominate too many of the world's major growing cities and mass slum clearance is planned (Reference 6) in most of these locations.

Population migration is another potentially significant factor. Global climate change is a fact and focus is rapidly moving away from trying to curb change to mitigation strategies. Many of the countries that are predicted to see continued population growth also face significant climate challenges. As a result of this, mass migration to the remaining temperate zones becomes a possibility. Countries less impacted by climate change that open their borders will face a huge challenge of accommodating these new "climate refugees". Not just housing but healthcare, retail and all the other service industries that prop up modern life.

So what might the high-rise typology of the future look like? Well, the prototype is starting to emerge. Traditional high-rise designs will not mix low income social housing with valuable office space or accommodation for the wealthy and if the office need is going to change anyway then a scheme like Sky-City by China Broad (Reference 7) starts to become a logical proposal. A place where someone can be born, live their life, work, find love, start a family, retire and die without ever needing to leave the Sky-City.

Currently planned to reach towards a 1km mark, how can you achieve safety, what are the performance based challenges and solutions for this type of building and what does a hyper-tall Sky-City which is 2km or 3km tall look like and can it be safe from fire?

可能的话，现有建筑可以翻新以适应新的办公文化的要求。中央商务区已具备良好的通讯网络，因此较易成为新型办公中心。在伦敦和纽约等主要城市中正在规划建造的塔楼群将成为最后一批塔楼，而在某些逐渐发展成熟的城市，如非洲和南美一些亚洲金融中心，这一发展趋势将会有所滞后，但最终将会发展到同样的阶段。

在住宅建筑方面，世界人口持续增长，但是增长速度正在放缓。依目前预计 (文献5)，全球人口水平将在95亿上下波动，但我们预计发展中国家和某些新兴经济区人口在一段时间内还将有所增长。在现有城市中建立富人高层住宅受到限制; 建造高层建筑的推动力通常是财政收入而并非刚性需求。但是低收入家庭仍有居住需求，世界大多数主要发展中城市仍被贫民窟主宰，不过在大部分上述贫民窟中已经开始清理计划的制定 (文献6)。

人口迁移是另一个潜在的重要因素。全球气候变化是一个事实，关注的焦点迅速由试图遏制变革转移到减灾战略。人口将持续增长的国家多数面临着巨大的环境考验，由此可能造成人口大规模迁徙至温带。这些"气候难民"的涌入，将使开放边界且受气候变化影响较小的国家面临巨大挑战，不仅包括住房问题，还包括医疗，商业以及和现代生活相关的各种服务行业。

那么未来的高层建筑会是什么样子呢? 雏形已然出现。传统的高层设计不能兼顾低收入保障房与高级办公或豪宅的功能要求。如果办公需求发生改变，中国远大集团的天空之城计划 (文献7) 将会是一个合适的方案。天空之城是一个人们出生、生活、工作、寻找爱情、建立家庭、退休和死亡都无需离开的地方。

如今，一些建筑计划修建高达一千米的建筑，如何实现其安全? 性能化设计的挑战和解决方案是什么? 如果超限高建筑天空之城高达两千米甚至三千米又将会是什么样子，能够保障它的消防安全吗?

超高层建筑设计以一个简单的塔楼为参考对象似乎是不太可能的，使用那么多支撑结构只是为了达到高度要求是毫无意义的。基础的形式可能会增加，更像锥形或者三角形的建筑将会出现 (文献8)。建筑的宽度将显著大于当今高层建筑，建筑周长将导致需要在其内部设计中庭或者开敞空间。

超高层建筑将凭借其高度优势提供与传统城市景观相同的使用空间。要设计的高层建筑是一个垂直融合社区，因此"建筑"消防策略的概念需让位于为城市规模项目开发制定的总体消防规划。这是消防生命安全工程师和审批机关角色转换的一个典范。

## 高层建筑性能化设计指标

要了解超高层建筑的性能指标，首先要考虑面临风险的主体是什么以及该风险随着从低层建筑到中等高度建筑，再到高层建筑，乃至超高层建筑 (见表1) 的过程中将如何变化。如果在最初考虑面临风险的人员，我们会发现超高层建筑的消防性能化设计指标如何伴随突发事件的风险而改变，以及由所提供的人员疏散宽度比例带来的人员疏散实际情况的改变。

整体上，我们将从低层建筑的整体疏散过渡到高层建筑局部疏散。极有可能在某一层发生火灾，人员可撤出了受影响的区域，但无需逃离到室外。这一情况类似于街区中发生火灾，人们可能不会撤离到距着火建筑几十米以外的地方。

由疏散至室外区域到疏散至建筑中其他区域的这一转变，尤其考虑到消防员的参与之后，具有非常显著的影响。为实施救援，消防员需要确保作业区内没有未受保护的人员。消防救援过程会产生高温烟气，造成大面积的污染，并造成缺乏防护服和呼吸器的人员死亡。

It seems unlikely that a simple tower would be the typology for a hyper-tall building. It makes little sense to use so much supporting structure just to attain height. Instead, the base form is likely to expand and forms that are more pyramidal or triangular in shape could emerge (Reference 8). The width of these buildings will be significantly greater than current tall buildings and that girth will lead to a need for atria or open spaces within the structure.

Hyper-tall, "mega-city" towers will feature the same range of occupancies across their height as we find in a traditional city scape. As we start to design tall structures that are vertical integrated neighborhoods, the notion of developing a fire strategy for a "building" has to give way to thinking about the way that master plan fire strategies are developed for city scale projects. This is a paradigm shift in the role for the fire & life safety engineer and the approving authorities.

## Performance Based Parameters for High-Rise

To understand what the performance based parameters are going to be for hyper-tall buildings, you can start by considering who is at risk and how that risk changes from a ground hugging building to a medium rise then tall and finally super or hyper-tall building (see Table 1). If we consider initially occupants at risk, then we can see how the performance expectations start to change with very tall buildings as the potential disruption from an event and the practicalities of evacuation due to the ratio of escape width to persons served as it starts to shift in very tall buildings.

Overall we move from a position in low-rise where the whole occupancy is evacuated to a position in hyper-tall buildings where only a small fraction of the population are moved, and there is a very real possibility for a fire at height that no-one would actually leave the building during a fire event, although they would move away from the area affected. This is the same as would happen in a fire within a city block where people may not move more than a few tens of meters away from the actual building where a fire has occurred.

The shift from evacuation "to outside" towards evacuation "to another place within the building" has very significant consequences, particularly when you consider the interaction with fire fighters. In order to carry out their operations, fire fighters need to have confidence that unprotected occupants are not in the part of the building they want to work in. Firefighting operations can result in widespread contamination by high temperature smoke which will kill those without protective clothing and breathing apparatus.

| Person at risk<br>面临风险的人员 | Building Form 建筑形式 | | | | |
|---|---|---|---|---|---|
| | Low Rise<br>低层建筑 | Medium- High-Rise<br>中等高度建筑 | Tall<br>高层建筑 | Supertall<br>超高层建筑 | Hyper Tall<br>超限高建筑 |
| **Occupant immediately effected by the fire**<br>处于着火区域的人员 | Must be made aware of the fire hazard quickly and move to a place of safety immediately.<br>必须及时发现火灾并立即撤离到安全区域。 | Must be made aware of the fire hazard quickly and move to a place of safety immediately.<br>必须及时发现火灾并立即撤离到安全区域。 | Must be made aware of the fire hazard quickly and move to a place of safety immediately.<br>必须及时发现火灾并立即撤离到安全区域。 | Must be made aware of the fire hazard quickly and move to a place of safety immediately.<br>必须及时发现火灾并立即撤离到安全区域。 | Must be made aware of the fire hazard quickly and move to a place of safety immediately.<br>必须及时发现火灾并立即撤离到安全区域 |
| **Occupant close to but separated from the fire**<br>与着火区域相邻区域的人员 | Should be made aware of the potential fire hazard quickly and move to a place of safety immediately.<br>应该意识到潜在火灾危险并立即撤离到安全区域。 | Should be made aware of the potential fire hazard quickly and move to a place of safety immediately.<br>应该意识到潜在火灾危险并立即撤离到安全区域 | Can be made aware of the potential fire hazard eventually and prepare to move to a place of safety.<br>意识到火灾危险，并且准备疏散到安全区域 | Can be made aware of the potential fire hazard quickly and prepare to move to a place of safety.<br>意识到火灾危险，并且准备疏散到安全区域。 | Can be made aware of the potential fire hazard quickly and prepare to move to a place of safety.<br>意识到火灾危险，并且准备疏散到安全区域。 |
| **Occupant remote from the fire**<br>远离着火区域的人员 | Can be made aware of the potential fire hazard quickly and prepare to move to a place of safety.<br>意识到火灾危险，并且准备疏散到安全区域。 | Can be made aware of the potential fire hazard quickly and prepare to move to a place of safety.<br>意识到火灾危险，并且准备疏散到安全区域。 | May not be made aware of the potential fire hazard and may remain generally uninterrupted by the fire incident if it is contained.<br>可能没有意识到潜在的火灾危险，如果所处区域在建筑内部，可能不会因为火灾而中断原有活动。 | Would not be made aware of the potential fire hazard and must remain uninterrupted by the fire incident if it is contained.<br>不会意识到潜在的火灾危险，如果在建筑内部，不会因为火灾而不会中断原有活动。 | Would not be made aware of the potential fire hazard and must remain uninterrupted by the fire incident.<br>不会意识到潜在的火灾危险，不会因为火灾而不会中断原有活动 |
| **Commentary**<br>注释 | The basis of the above is that disruption to occupants is limited so it is a simple matter to evacuate people to mitigate the hazard from the fire.<br>上述的基础是对人员的打扰是有限的，并且疏散人群减小火灾的危害是简单可行的。<br><br>People who are remote such as those in neighboring buildings do not need warning but eventually could be moved if necessary as again the disruption is small and the mechanisms to move people are simple.<br>远离火源的人员 (如相邻建筑中) 无需被警告，但是必要的时候也会需要疏散，<br><br>Compartmentation requirements may be limited and occupants can typically self rescue by evacuating quickly or climbing from the building if necessary.<br>防火分隔的要求可能受到限制，必要时，人员通常可以采取自救，迅速撤离或者爬到楼顶。 | With medium rise buildings, we are beyond the height at which self rescue is a possibility without using a protected internal core.<br>中等高度建筑已经超过了无需受保护的内核即可自救的高度限制。<br><br>It therefore becomes important to evacuate people who may not be at risk initially but could become at risk if the cores fail.<br>因此，疏散最初未受到火灾威胁但是未来会受到火灾影响的人员非常重要，<br><br>The disruption is moderate, but the balance between the likelihood of a fire and the disruption makes precautionary evacuation of those remote from the fire a sensible option.<br>破坏是中等程度的，但是，火灾的可能性和破坏程度之间的平衡，使得远离着火区域的人员的预先疏散成为明智的选择。 | With a tall building, disruption from a fire becomes a major problem. The number of persons potentially at risk starts to rise significantly and a careful controlled, phased evacuation becomes important.<br>在高层建筑中，火灾的危害成为最大的问题，处于火灾潜在风险中的人员的数量显著增加，需要认真控制的阶段疏散变得至关重要。<br><br>So starting with those most at risk and then cascading out to those less or not initially at risk evacuation will progress. Some persons a long way from the fire may have some movements restricted, but need not be told of the actual fire event until it is their turn to evacuate, if the emergency lasts that long.<br>开始疏散最危险的人员，然后疏散较危险或者最初并未处于危险之中的人员，如果疏散持续时间很长，某些远离火源的人员可能行动会有所限制，直到轮到他们疏散的时候才告知火灾的发生。 | As the height and complexity increases, so the potential disruption becomes severe. Also, the capacity of escape cores as a ratio of the total occupancy starts to approach the point where you cannot evacuate all people in a meaningful time period. With the use of elevator egress and careful management a full building evacuation remains possible, but is a very protracted process and difficult to achieve.<br>由于高度和复杂程度的增加，潜在的破坏变得更为严重。此外，作为一部分人员疏散的逃生通道的容量开始达到顶峰，无法疏散全部人员。依靠电梯疏散并精心组织，建筑整体疏散还有可能，只是这是一个冗长并难以实现的过程。 | As the height and complexity continues to increase, so the potential disruption becomes severe. Also, the capacity of escape cores as a ratio of the total occupancy reduces so you cannot evacuate all people in a meaningful time period.<br>由于高度和复杂程度的增加，潜在的破坏变得更为严重。此外，人员疏散的逃生通道的容量降低，无法疏散全部人员。<br><br>It is inevitable that some people will not be evacuated and hence preventing fire spread becomes paramount.<br>不可避免的是有些人将无法疏散，因此，防止火灾蔓延变得极为重要。 |

Table 1: Variation Of Occupant Response Performance Parameters By Building Height
表1: 人员响应性能参数随建筑高度发生的变化

In a commercial office building, it is possible to train occupants to act in a specified preferred manner in the event of a fire. Once you start to change the occupancy types to include the same mix as a regular city, then you start to see challenges in compliance and information dissemination. Consider for example the difference between an army base and a town. In an army base you can send out public address messages and expect compliance, in a town, you cannot readily do that. The same difference happens between the homogenous commercial office tower (the army base) and a hyper-tall, mega-city tower (the town scenario).

The consequence of people staying in the building, firefighting operations overlapping with occupation and the challenges of compliance mean that it becomes increasingly hard to make the sort of assumptions that underline traditional codes. For example, rather than assuming that occupants will leave a building or that they will stay in a building in a place of refuge, it becomes necessary to start to think about the possibility that some people may leave, some may stay and some may wait for a while and then leave. This represents a significantly more challenging fire safety environment.

The simplistic timelines often drawn to help understand ASET vs RSET in a performance based design become defunct and the analytical process becomes significantly more complex and challenging.

## The Legacy Challenge

One of the key differences that a performance based approach to fire & life safety design delivers is the opportunity to consider not only the building when it is first constructed, but to question what future legacy changes may need to be considered. When developing a solution for a hyper-tall, mega-city structure this becomes fundamental to the project.

It is overly simplistic to assume that the entire building use will be defined and static for the design period of such a large project, let along during construction or over the lifetime of the building. In the same way that cities change and evolve over time, so a hyper-tall tower will be in a state of constant flux.

The process of churn in the building use and occupancy will create additional challenges for the fire safety strategy. It isn't possible to pick up a code and design the building to meet it as the occupancy characteristic for part of the building will change over time. Instead the building has to be designed like a city grid which different uses can plug into through its lifetime.

Some of the challenges that face high-rise buildings compared to low-rise properties may not be accentuated by hyper-tall, mega-cities. For example, water supplies would have to be distributed around the building for practical purposes anyway rather than pumped to height in one long lift, so fire pumps and the suchlike need not change that much.

## Derived Solutions

It is clear that hyper-tall, mega-cities will require performance based approaches of a city scale, not prescriptive code solutions at a building scale. However, this does not mean we cannot already address the challenges that result from this.

商业办公建筑中，可以培训员工使其在发生火灾时按照明确的最佳方式逃生。如果考虑到不同的人员种类，就会面临不同行为反应和信息传播的挑战。试以军事基地与城镇的区别为例，在军事基地中，可以发送广播消息并等待执行，这在城镇中却很难做到。同样的区别存在于商业塔楼 (陆军基地) 和超限高层塔楼 (城镇) 之间。

人员停留在建筑内、消防救援行动同使用共存的结果和合规性的挑战很难按照传统规范的说明作出假设。举例来说，不能简单认为人员全部疏散至室外或者全部疏散至避难层，而有必要考虑部分人员撤离、部分人员停留、以及部分短暂停留后撤离等多种可能性，这为火灾安全环境提出了新的挑战。

性能化设计中的ASET与RSET时间线已不存在，分析过程变得更复杂且更具有挑战性。

## 对传统的挑战

性能化设计和消防与生命安全设计相比主要区别是，性能化设计不仅考虑建筑初建时会遇到的问题，也考虑未来可能发生的变动。在探索超限高层建筑的消防安全解决方案时，这是至关重要的。

对于大型建筑项目，假设其使用功能在建筑设计、施工乃至整个寿命周期均不发生改变的做法过于简单。同样，城市在随着时间不断变化发展，超高层塔楼也将保持不断进步。

建筑使用功能的改变将为消防安全策略提出新的挑战。由于建筑中某些区域使用功能会随时间而改变，很难有哪部规范，建筑设计可完全满足其要求。因此，须将建筑设计成城市网，利用模块化的设计，这样便可以在建筑整个寿命周期内实现不同使用功能的增加。

与普通低层建筑相比，高层建筑面临的某些挑战可能并不会增加。例如，供水系统需要根据实际用途分区设置，而不是通过竖井抽吸到不同高度，因此，消防泵和诸如此类的设备无需进行很大改变。

## 解决方案

很显然，超高层建筑需要一个城市规模的性能化设计方法，而不是依据一栋建筑规模的条文式规范寻求解决方案，不过，并不意味着我们无法应对由此带来的挑战。

在消防安全解决方案中，更趋向于应用新的建筑类型来活跃思维，这并无害处，并且值得鼓励。尽管如此，创新应该切合实际，并且应该建立标准以保证预期功能的实现。

就如空间站和潜艇，其空间的建立是人类努力的成果，其消防安全问题仍被考虑在其中。火灾事件从根本上是由留在船上但转移到安全地点的人员处理的，某些情况下还会使用灭火介质。

如果可以找到这些极端条件下仍可采用的方法，那么它将可能成为实现超高层建筑消防安全的最新技术。

我们可以离开整体疏散的想法，并且目前的疏散方法并非完全不可采用。人员从危险区域通过楼梯安全疏散依然是一种高效可靠的方法，但更重要的是兼顾垂直疏散和水平疏散。正如现行规范中认识到的，跨越防火分区的疏散和垂直疏散同样重要。在有必要进行长距离垂直疏散的情况下，采用电梯疏散可能更合适，但是也不能使人员下降两千米到达安全地点。

It is tempting to use a new building typology to stimulate radical thinking in fire safety solutions. There is no harm at all in this and innovation should be encouraged. However, innovation should have due regard to practicality and established norms to ensure that the desired functionality is achieved.

Spaces such as a space station or submarine are at the very extreme of human endeavor but the problems of fire safety have been thought through and a fire incident is fundamentally tackled by personnel remaining on board but moving to a safe location and in some cases applying extinguishing medium.

If solutions can be found to operate at these extreme conditions, then it seems likely that current technology can be extended to achieve safety in a hyper-tall mega-city.

Removing the expectation of total evacuation and it is unlikely that current escape solutions would become outdated. Stairs remain a highly effective and reliable solution to move occupants safely away from the area most at risk but it may become more important to consider horizontal movement as well as vertical movement. Cross compartment evacuation, as recognized in many existing building codes is likely to become almost as important as vertical movement. Where extended vertical movement becomes necessary some lift evacuation may be appropriate, but it seems unlikely that you would want to move occupants 2km to safety down a hyper-tall tower.

Firefighting for traditional tall buildings generally relies on fire fighters from the surrounding city area arriving at the tower base and then transferring equipment and personnel up the building. In a hyper-tall mega-city, the principle of adopting a city master plan approach becomes critical with regards to firefighting. It is expected that fire stations would be placed throughout the building to ensure rapid deployment and limit the need for excessive vertical movement.

Small firefighting vehicles and equipment may be needed to carry rapid response teams within the building and firefighting water supplies may need to take into account a wider range of applications as traditionally internal firefighting water provisions have been tuned to compartment firefighting.

Firefighting robotics is an area currently under much investigation with projects like the US Navy SAFFiR project (Reference 9), and there may be a role for semi-autonomous or remote firefighting tools to be developed. Firefighting drones to attack fires externally and remote compartment firefighting machines or similar could provide useful support to fire fighters in a hyper-tall mega-city. However, it is difficult to comprehend such systems meeting the adaptability of human fire fighters but they could become vital first aid fire fighters.

At the moment, tall building fire safety is critically reliant on fire suppression and compartmentation. Current fire suppression reliability may not be adequate, even in supertall buildings. Resolving suppression resilience need not require a radical rethinking of fire suppression. However, an overhaul of how suppression may be delivered and how existing components may be joined together in novel ways to deliver resilience will be necessary for hyper-tall buildings. In the same way that firefighting main designs achieve resilience to protect water supplies in an on-street scenario, so might suppression mains need to be designed in future hyper-tall buildings.

传统高层建筑消防灭火通常依赖于消防员，他们从城市周围赶到火场，并将设备和人员送到建筑上。在一座超高层建筑中，采用城市规模的战略原则对有效灭火是至关重要的。消防站应遍布于整个建筑，以确保火灾发生后快速部署并尽量控制垂直方向操作的需要。

建筑内部可能需要小型消防车和设备运载快速反应团队，由于传统的室内消防用水将转变成为防火分区消防用水，消防供水系统需要扩大应用范围。

消防机器人是 一个新兴领域，目前正在接受美国海军萨菲尔等项目 (文献9) 的众多审查，将有可能研发半自动或远程灭火工具。应用消防无人机在建筑外部灭火，使用空间隔离或相似设备可以为超高层建筑灭火提供有力支持。尽管很难了解这些系统是否能达到同消防队员相同的灵活性，但是他们能够成为重要的急救队员。

目前，高层建筑消防安全很大程度上依靠于灭火和防火分隔措施，而当前，特别是超高层建筑中灭火措施可靠性并不高。解决灭火系统的适用性不必对灭火系统进行重新思考及提出对灭火系统的彻底革新，基于现有系统，以新的方式结合并提高性能，对于超高层建筑尤为重要。通过同样类似的方法，加强消防主干管的可靠性，在未来超高层建筑中起到更好的作用。

最后的挑战是如何设置防火分区。在传统的城市布局中，我们将建筑分成不同区域以防止火灾蔓延。而建筑使用者和设计者希望光线和新鲜空气可以进入到建筑中，但设置的开口却会成为火灾传播的途径。为阻止这种风险，建筑被分隔开来。

如果我们将城市的概念应该用到超高层建筑中，通风和照明的需求依然存在，提供防火分隔却是一个巨大挑战，源于不得不考虑火灾在垂直方向的传播，加之分隔建筑意味着将丢失成本高昂的结构空间。

天空之城设计中已经采用了一些方法，目的是在模块间实现高水平的防火分隔。这种方法在单一重复的模块方案设计中很有效，但是若要跨越超高层防火分区或者划分更大的防火分区，这种办法可能就失效了。认识到在设计伊始或施工过程中，被动防火保护和防火分隔的设置并非一成不变也很重要。施工多年后，参观一座完成的建筑都很可能在分隔处发现孔洞，由此看来，切实的保持分隔是项非常艰巨的任务。

作为性能化设计方法的一部分，确定火灾中结构的稳定性指标是十分重要的。传统设计中的简化标准仅考虑了单独结构元件，不适用于超高层建筑。超高层建筑中，结构要素之间的相互影响至关重要，需要增加结构冗余以确保部分构件失效不会对其他部分造成严重影响。按照规范要求甚至更高的耐火时间进行设计不一定是正确的方法，相反，设计时应该考虑火灾造成的结构失效，这种失效将如何导致火灾蔓延，以及对整体结构进行保护免于失效。

## 结论

本文很难逐一详细介绍超高层建筑消防性能化设计中的所有方面，但是希望借此提出对未来设计的挑战，相信应用目前的消防安全技术，结合性能化设计方法合理定义火灾风险，可以提供解决方案的方向。

One final challenge to consider at this time is compartmentation. Within the traditional cityscape, we separate buildings to prevent fire spread. Building users and designers want light and air to enter the buildings, but the openings used for these purposes can provide a route for fire spread. To counteract this risk, buildings are separated.

If we translate the city scape into a hyper-tall mega-city, the need for ventilation and light remain, but it becomes a huge challenge to provide fire separation not least because we have to consider fire spread in the third, vertical dimension, but also because separating elements of a building could mean costly lost volume within the structure.

Something that the Sky-City design has done is to achieve a high level of fire compartmentation between each module. This approach has validity in a scheme designed around repetitive modules, but if you want more variety across the hyper-tall mega-city or larger compartments, the solution may become invalid and some form of separation based fire resilience may become necessary. It is also important to recognize that passive fire protection and compartmentation achieved in the original design or construction of a building cannot be assumed to be static for the lifetime of the building. Anyone who has visited a completed building a few years after construction will find holes in compartmentation. The task of maintaining such compartmentation can be extremely onerous.

As part of a performance based approach it is important to define the structural fire stability expectations. The simplistic criteria used for traditional design consider structural members in isolation and are not satisfactory for a hyper-tall mega-city design. The interaction between structural elements becomes critical and structural redundancy has to be significantly increased to ensure that a failure of safety in one small part of the mega-city does not have a disproportionate and catastrophic impact on other parts. Designing for a specified or even a higher fire resistance period may not the right approach and instead, the design should consider structural failure by fire, how this might lead to further fire spread and how the overall structure can be protected from local failure.

## Conclusions

It is not possible to cover every aspect of performance based design for hyper-tall building in one paper, but it is hoped that a sense of the challenges has been given and also some confidence that current design tools exist to adequately assess safety whilst current fire safety technology could be adapted to provide solutions, provided that the necessary performance based approach has been taken to properly define the hazards.


### References (参考书目):

[4]**Final Reports from the NIST Investigation of the World Trade Center Disaster**. (2005). NIST.

[6]**An Integrated Development Plan for Mumbai**. (2010). Lalit Gandhi, Mayank Gandhi, Remaking of Mumbai Federation. CTBUH Mumbai.

[1]Reddaway,T. (1940). **The Rebuilding of London after the Great Fire**.

[8]**Shimizu Corporation**. http://www.shimz.co.jp/english/theme/dream/try.html

[7]**Sky City, the Positive Energy**. Zhang Yue BROAD Group. July 31, 2013

[3]**Technical Report, Interstate Bank Building Fire**. United States Fire Administration

[2]**Tribunal of I nquiry on the Fire at the Stardust, Artane, Dublin on the 14th February, 1981** (1982). Government publications. Pl.853. Dublin: Stationery Office. Retrieved 28 November 2013.

[9]US Navy Office of Naval Research, **Shipboard Autonomous Firefighting Robot**. August 2011.http://www.onr.navy.mil/~/media/Files/Fact-Sheets/34/Shipboard-Autonomous-Firefighting-Robot.ashx

[5]**World Population 2012 Revision**. Department of Economic and Social Affairs Population Division. United Nations. August 2013.