Windows, Comfort, and Resilience

Graham S. Wright, Ph.D., Senior Scientist, Passive House Institute US

Abstract

This article addresses four windows-related questions which the PHIUS Certification staff and Technical Committee have encountered since the advent of the *PHIUS+ 2015 Passive Building Standard – North America*, in March 2015. These concern the requirements and recommendations for window performance in building projects seeking certification, whether a mechanical cooling system should ever be required, and whether, for large buildings whose space conditioning needs are "internal-gain-dominated" as opposed to "shell-dominated", the lower R-values required to meet the overall building performance criteria have an impact on the resilience or passive survivability.

1 Introduction

The basic function of buildings is to shelter us from "the elements" – chilling winds, rain, and frost, scorching sun. That is, their purpose is to provide a place more comfortable to us than the local above-ground planetary environment. For most of history and pre-history, the comfort improvement was provided by passive measures such as roofs, walls, operable shutters, with the only "active" energy system (if any) being solid-fuel combustion heating in cold weather. Mechanical ventilation did not appear until the fossil-fuel age began in the 19th century. In terms of indoor air temperature, the acceptable range was evidently rather wide, with temperature near the skin more closely controlled by a lot of adjustment in clothing.

The early 20th century saw the invention of mechanical cooling, with electrically-driven "heat pumps" that could also be used for heating. With mechanical systems and cheap energy to run them, it became practical to control the interior air temperature and humidity in a narrow range for a building of any form, anywhere, all the time. Responsibility for interior comfort shifted from architects to mechanical engineers, and a whole range of architectural techniques for passive comfort, cooling especially, fell out of favor. Air-conditioning was originally justified by increased factory and office productivity, but by the 1960s became part of the American standard of living more generally. Interior air comfort standards narrowed – for example the heating set point in Building America House Simulation protocol (2014) is 71 F and the cooling set point is 76 F.

The oil price shocks of the 1970s however, sparked a counterrevolution in favor of passive building design. The initial focus was on the use of passive solar gain for cold-climate heating, with thermal mass to stabilize the temperature. By the early 1980s though, a good case had been made that minimizing heat losses was more to the point than maximizing gains, and the cold-climate package of measures that we recognize today as "passive house" came into focus: super-insulation (including windows and thermally-broken construction details), super-air-tightness, intentional ventilation, often with heat recovery, and a moderate amount of solar gain with little or no extra thermal mass.

This latter-day passive building movement then, was not and is not a straightforward revival of the pre-fossil-fuel way of living and building. The difference consists in the desire to maintain those higher standards of interior comfort, but use much less energy. Energy-intensive machinery made them possible, but the modern idea of a passive building is one that can maintain a high standard of indoor comfort with much less operating energy and much smaller mechanical systems than has been typical through the age of cheap fossil fuels. It is in this newer, post-1979"tradition"that the Passive House Institute US (PHIUS) does its work.

A passive building in this latter-day sense, should have very low peak heating load and peak cooling load, that is, it should be able to keep the interior temperature in about that 70 to 76 F range with just a small low-power heating and cooling system – this is a signature feature. Such a design generally provides two notable benefits for the occupants – low energy bills (in normal operation), and passive survivability (during outages). For not-large buildings in most climates a low peak load design requires a lot of insulation to reduce heat transmission. Windows and doors are weak links – R-7 is quite bad for a wall, but very good for a window, and for typically-sized residences in most climates, high-performance windows are also a crucial part of a low-peak-load design.

A third benefit of those high-performance windows has to do with thermal comfort (again in normal operation.) In addition to the air temperature, the temperatures of the interior surfaces surrounding the occupants affect their thermal comfort, and highly insulating windows keep the inside surfaces warmer in the winter. Compared to an old house with R-1 windows then, we can claim that a passive house is more comfortable at the same air temperature, or that some more energy may be saved by not controlling the air temperature quite as tightly without sacrificing any comfort. [1]

Protecting this "comfort claim" was deemed important enough that it was incorporated as a constraint in the development of the PHIUS+ 2015 Passive Building Standard. The overall approach taken was cost-optimization to find the point of diminishing returns on investment in the building envelope and other passive measures. But the windows for the simulated study buildings were chosen not based on cost-effectiveness but with R-values high enough to maintain a 60 F surface temperature on the interior of the glass, at a winter temperature extreme for the climate (12-hour mean minimum). Because there is a close connection between high-performance windows, comfort, and low peak load, PHIUS+ 2015 carries the comfort benefit indirectly, by limiting the peak loads. That is, the peak load limits are *predicated upon* windows good enough to deliver on the comfort claim, but the standard does not have a separate comfort-based requirement for window performance (only recommendations).

1.1 Questions (with short answers)

Over the course of the 18 months since the full launch of PHIUS+ 2015, a number of questions related to windows, comfort, and resilience have come up, and were considered by the PHIUS Technical Committee, and certification staff. That number is four. Those questions are listed below along with the short version of the answer. Longer answers appear in the succeeding sections.

1. **Should a Comfort-based Requirement be imposed on minimum interior surface temperature? –** No, only moisture-based requirements.
2. **What is the basis of the 16 C (60.8 F) minimum surface temperature recommendation for comfort given in the training, and do I really need windows that good?** – That threshold can

[1] Note though, that in warm *daytime* conditions the inside surface of a triple-pane glazing can be warmer than that of double-pane glazing, warmer even than the outside air temperature. Thus, in hot climates super-windows may face a tradeoff between comfort and energy savings, rather than being definitely helpful for both, as they are in cold climates.

be derived from the human comfort model referenced in the comfort standards ISO 7730 and ASHRAE 55. One can "get away with" lower performing windows the fewer of them are used. For demographic reasons higher comfort standards are advisable for residential than non-residential.

3. **Should there be a Requirement for a cooling system? –** No, but a recommendation can be made based on the limits of the adaptive comfort model. Again, adaptive comfort is more justifiable for non-residential and cooling systems are advisable for residential.
4. **Does the resilience benefit stay intact for large buildings? –** Sometimes; enough glass will compromise it, and more-exposed corner and edge units are more vulnerable.

2 Answers (longer)

2.1 Moisture-based Requirements on interior surface temperature

In most opaque areas of the building envelope, thermal bridges must be mild enough such that the relative humidity on the interior surface stays above 80%, so as to avoid mold growth.

For low-thermal-inertia elements such as windows and doors, they must be insulating enough to avoid outright condensation (100% RH) on the inside surface.

The assessment protocol generally follows ISO 13788 and supporting spreadsheet calculators are available.

2.2 Comfort-based Recommendations on interior surface temperature

It turns out human comfort is a moderately deep subject. The "4C delta" guideline is a simplification.

The main standard metrics for overall bodily comfort are Predicted Mean Vote and Predicted Percent Dissatisfied (PMV/PPD). This was developed in 1970 and is explained in the standard ISO 7730. That standard suggests three possible categories A, B, C in terms of design goals, corresponding to 5, 10, and 15% dissatisfied. ASHRAE 55 also refers to the PMV/PPD system and specifically picks the 10% dissatisfied as the pass/fail level. [2]

With the PMV/PPD metrics, one must be specific about the occupant's metabolic activity and clothing level.

In the example below in Table 1 - calculated with the ASHRAE Comfort Tool (screenshot in Figure 1) - the Mean Radiant Temperature (MRT) is decoupled from the air temperature, and indeed the PPD crosses the 10% threshold from Neutral to Slightly Cool at a 4C delta. Going warmer it crosses the 10% dissatisfied threshold at a 3C delta.

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[2] ASHRAE has a handy standalone software tool for doing these comfort calculations. $117 now at https://www.ashrae.org/resources--publications/bookstore/thermal-comfort-tool

Also, the Center for the Built Environment at the University of California Berkeley has an online "CBE Thermal Comfort Tool" at http://comfort.cbe.berkeley.edu

Both tools do PMV/PPD calculations but have different added features – the ASHRAE tool can do more detailed calculations of the Mean Radiant Temperature (MRT) depending on room and window geometry. The CBE tool has a "SolarCal" function to adjust the MRT for the effect of direct sunlight.

There are also four different radiant temperature asymmetry criteria, and maintaining less than a 5C delta satisfies all of them.

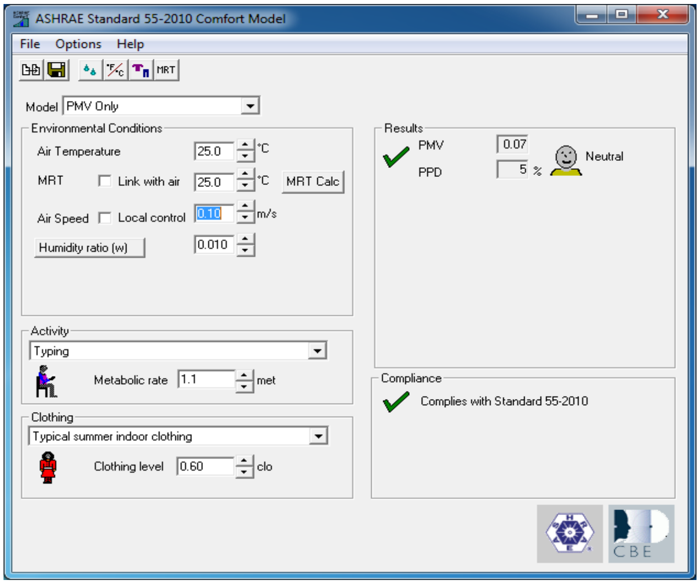


Figure 1. Nominal example - Neutral comfort conditions by Predicted Mean Vote.

Table 1. Nominal example – radiant temperature effect on comfort.

Air Temp [C]	MRT [C]	Air speed [m/s]	Humidity Ratio	Metabolic Rate [met]	Clothing Level [clo]	PMV	PPD [%]
25	25	0.1	0.010	1.1	0.6	+0.07	5
25	21	0.1	0.010	1.1	0.6	-0.50	10
25	28	0.1	0.010	1.1	0.6	+0.52	11

There are a couple of other things to mention vis-a-vis other things PHIUS teaches. On the one hand, with regard to the effect of windows dragging down the MRT in the winter, that effect is diluted because even standing in a corner near large windows, the view factor to the glass is not 100%; the surrounding warmer opaque surfaces still have a lot of influence. On the other hand, notice that for neutral comfort at that clothing level, the required temperature is 25 C, not 20 C, so if we are designing with an air temp of 68 F (20 C) then we use up some, maybe all of the comfort margin for surface temperatures, depending on clothing and metabolism. These two factors somewhat offset each other and therefore a 4C guideline is arguably still reasonable in general.

Another consideration is that the PMV/PPD metrics are based on healthy adults, and according to ISO 7730 were developed specifically for the work environment, so one argument for keeping surface temperatures more moderated is in case of frail/sensitive people. This point was made rather emphatically by Robert Bean (2015), "How easy is 'adaptive comfort' and natural ventilation for some one with arthritis, MS, Parkinsons, cerebral palsy? How easy is programming thermostats and HVAC maintenance for someone with macular degeneration, cataracts, early Alzheimers?" In a nonresidential workplace environment, the assumption of healthy adult occupants is likely valid, but residences are more likely to be occupied by more-sensitive young, old, and medically challenged people.

2.3 Evaluating whether a building design should have a cooling system

As noted in the intro, our concept of passive building is not a straightforward revival of the pre-fossil-fuel way of living and building. Nevertheless, the older ways still have something to teach us on the summer-comfort front. (The early 1980s development of the concept took place in cold climates in the US and Canada. The period of European deployment that followed in the 1990s also focused on a cool temperate climate.) Some designers are quite set against the use of cooling systems, and indeed, with regard to the building code, the "cooling-is-a-luxury" perspective survived the introduction of air-conditioning – North American building codes do not require a cooling system in any climate, nor do the U.S. Energy Star requirements which are part of the PHIUS+ certification program. [3]

The question of when to design in a cooling system could be decided with reference to ASHRAE 55. Clause 5.4 lays out the procedure for determining Acceptable Thermal Conditions in Occupant-Controlled Naturally Conditioned Spaces, based on the climate.

Basically, one looks at the daily mean outside temperatures in the hottest part of the year, calculates a running average, and then from a graph/formulas determines the acceptable range of indoor operative temperature, which cannot be any higher than 89 F regardless of climate. The formula for the upper limit is 0.31 * Tpma-out + 60.5 F, where Tpma-out is the "prevailing mean outdoor temperature". Tpma-out must be less than 92.3 F. (There is also a lower limit which is 12.6 F cooler.) Up to another 4.0 F can be added to the upper limit if increased air speed of 236 fpm can be provided (with fans).

The way to apply this would be to plug that upper-limit temperature into the building energy model as a cooling set-point, and see if there is any cooling load remaining. If there is, then a cooling system is advisable.

For the Tpma-out calculation the language of ASHRAE 55 prefers TMY3 or actual daily weather data, but monthlies are allowed if those are not available. Seven to thirty days of averaging is acceptable. For example in Dubuque, Iowa, picking in the middle at 18 days (432 hours) and running the average, Tpma-out tops out at 73.9 F which is a little warmer than the 70.2 max in the monthly file.

This makes the upper operative temperature limit (Top):

Top = 0.31 * 70.2 + 60.5 = 82.2 F, by monthly data

Top = 0.31 * 73.9 + 60.5 = 83.4 F, by TMY3 18-day running average

Going by the monthly, then with the air speed adjustment the limits are

Top = 82.2 + 2.2 = 84.4 F, for air speed 118 fpm

Top = 82.2 + 3.2 = 85.4 F, for air speed 177 fpm

[3] With respect to the thermal environment, the 2012 International Building Code simply says that the building must be provided with "an active or passive system capable of maintaining an indoor temperature of not less than 68 F, three feet above the floor, on the design heating day." The National Building code of Canada is similarly straightforward but with a higher temperature – "required heating facilities shall be capable of maintaining an indoor air temperature of not less than 22°C (71.6°F) in all living spaces."

Top = 82.2 + 4.0 = 86.2 F, for air speed 236 fpm

It may be fair to credit the 118 fpm if there are any ceiling fans – probably it is not too difficult to get this much air speed. U.S. Energy Star ratings for ceiling fans report air flow in cubic feet per minute, which can be converted to fpm directly under the fan using the fact that the test duct is a cylinder eight inches larger in diameter than the fan. Air speed in the room could be then estimated from consideration of the room cross section compared to the fan.

Thus, a draft protocol could be written as follows:

A cooling system may reasonably be foregone if:

- Representative occupants have metabolic rates ranging from 1.0 to 1.3 met.
- Representative occupants are free to adapt their clothing to the indoor and/or outdoor conditions within a range at least as wide as 0.5 to 1.0 Clo.
- The prevailing mean outdoor temperature Tpma-out (monthly max) is greater than 50 F and less than 92.3 F.
- WP/PHPP model calculates no cooling load with a cooling set point of 0.31 * Tpma-out + 60.5 F, plus 2.2 F if there are ceiling fans.

The conditions on the representative occupants might always be assumed true for residential, but might not be for nonresidential. However, as noted above, residential occupancies are demographically more likely to be occupied by sensitive people than workplaces, so a cooling system is more strongly advisable for residential.

2.4 Thermal resilience – quantification and examples

Passive buildings should feature low peak (design) loads for heating and cooling. This feature is associated with a "long thermal time constant". An attendant benefit of that is "thermal resilience" or "passive survivability," meaning that the indoor temperature stays within a tolerable range even during a utility outage.

Last year, at the behest of the New York State Energy Research and Development Agency (NYSERDA), the author developed a preliminary method for quantifying the thermal resilience of a building design, and applied it to a single-family residence pilot project designed to the PHIUS+ 2015 standard – "Staten Island B3.5" in the PHIUS project database, climate of Newark, NJ.

In brief, the idea was to run a dynamic simulation (in Wufi Plus) of the building for a period of time including both summer and winter, and subject it to outages of a fixed duration, which could occur at random with a constant probability per unit time (but could not overlap). The "rating" metric then was the range of interior temperatures during the outage hours. Initially, the outages were 36 hours, the simulation ran one year using a TMY3 climate file, and the total range of the interior temperature was noted. Later, with Hurricane Sandy in recent memory, the outage duration was increased to five days.

Using this method, a comparison was made to a code-minimum version of the same building. The passive house design performed much better, experiencing an interior temperature range of 42 to 91 F during the outage hours, while range for the code-minimum design was 24 to 100 F.

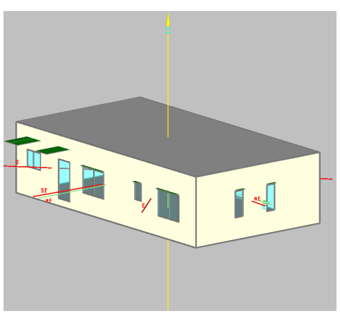
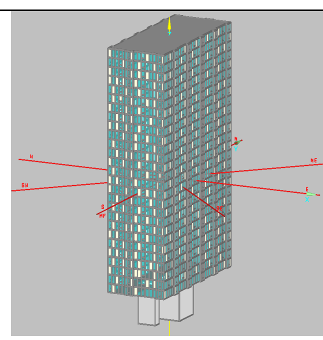
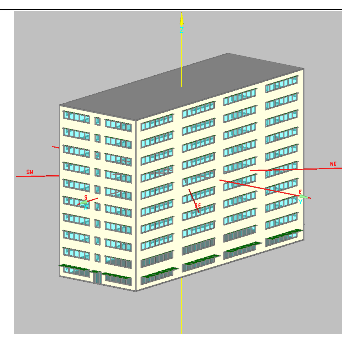
It was noted that under this procedure the total range of the interior temperature was sensitive to whether or not an outage coincided with the worst weather of the year, therefore, a climate file of 10 years of actual weather data was constructed, and the "rating" was modified to be the 0.5% to 99.5% range instead of the total range. By that method, the "5-day outage resilience rating" for Staten Island B3.5 was 45 to 88 F. This seemed plausibly survivable.

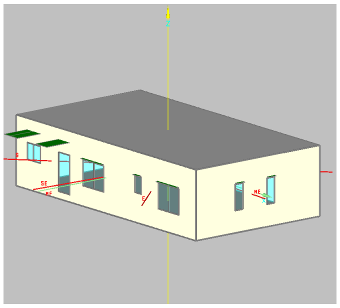
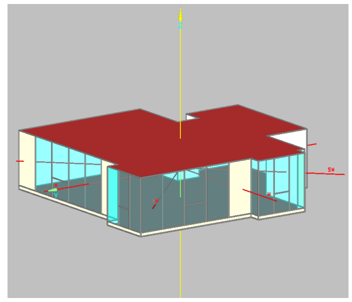
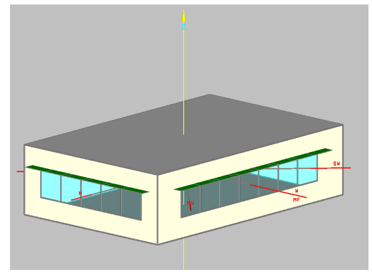
During the outages, the heating and cooling systems were shut off, and the internal gains dropped to those from the occupants only (no lighting or equipment gains). The occupancy was taken to be "full occupancy" according to Building America House Simulation protocol (2014). "Mechanical ventilation" was assumed to continue at the same rate, but there was no heat recovery, that is, it was assumed that some small fan or window operation was contrived to provide the normal minimum amount of fresh air (and its attendant heat loss or gain.)

Also, an hourly schedule for natural ventilation cooling by windows was obtained from a twin model of the building constructed in BEopt and using the same TMY3 climate file. (Wufi Plus lacks a state-sensitive window opening algorithm, though it has one for shading device operation.) The BEopt model was also used to size the heating and cooling systems according to ACCA manual J. For the 10-year simulation, the same one-year hourly natural ventilation file was reused over and over. Effectively, this means the occupants were modeled as using natural ventilation in a seasonally appropriate way, but on an hour-to-hour basis could make "mistakes" – mistakes that might or might not be psychologically realistic for humans, as opposed to this robotic procedure. s

This year, the method outlined above was applied to the question of resilience for larger buildings. Right now, the PHIUS+ heating and cooling criteria are set in terms of energy per unit of floor area regardless of building size. Thus large buildings, with a lot of floor area relative to envelope area, can be certified with lower R-values than smaller buildings in the same climate. This raises the question as to whether something is lost on the resilience front. Two cases were studied – an edge unit of a proposed high-rise in Chicago, and a top corner unit of one of the U.S. Department of Energy's Commercial Prototype Building Models – the high-rise apartment building, located in Staten Island / Newark. For both of the towers the whole-building models were upgraded to meet PHIUS+ 2015 as well. These are compared with the single-family in Table 2.

Table 2. "Thermal resilience" case studies.

	"Staten Island B3.5"	**"West Lake Tower"**	**"DOE High-Rise Apt. Bldg."**
Whole building visual			
Climate	Newark, New Jersey	Chicago, Illinois	Newark, New Jersey
Stories	1	32	10
Orientation	Long side Southeast	Short side South	Short side South
Whole bldg. annual heat demand	3.5	5.9	4.7

	"Staten Island B3.5"	"West Lake Tower"	"DOE High-Rise Apt. Bldg."
[kBtu/ft2]			
Whole bldg. peak heat load [Btu/ft2.h]	4.4	4.7	3.9
Dynamically Modeled unit visual	 Whole house	 Northwest **edge** unit	 Top floor Northwest **corner** unit
Interior floor area [sf]	1127	1127	912
Bedrooms	4	2	2
Outage occupancy	3.23	2.47	2.47
Ventilation [cfm]	49	34	52
Average Infiltration [cfm]	8.2	9.8	2.1
Window/wall ratio	10%	75%	30%
Window R-value [IP]	**8.4**	**4.5**	**3.1**
SHGC-COG	0.5	0.25	0.24
Shading - winter	0.5-0.8	0.7	0.6
Shading - summer	0.3-0.8	0.5	0.5
Exterior Wall	5.6 inch polyisocyanurate over 8 inch aerated concrete, **R-44**	Insulated concrete form, 6 inch concrete, **R-10**	XPS over steel stud wall, **R-23**
Roof	Cellulose, **R-97**	N/A	SIP, R-26
Foundation	5.3 inch polyisocyanurate over 8 inch aerated concrete, **R-40**, on piers	N/A	N/A
Internal mass	None added	Intermediate floor and ceiling 3.75in concrete, light interior walls 604 sf, furnishings 8 lbs/sf, modeled 152 sf	Floor to nbr 2 inch concrete over cellulose, interior partition walls 504 sf of double 5/8 drywall, furnishing 8 lbs/sf, modeled 150 sf
"5-day outage resilience	45 to 88 F	34 to 88 F 39-89 F with R-7 windows	30 to 86 F 34-87 F with R-7

	"Staten Island B3.5"	"West Lake Tower"	"DOE High-Rise Apt. Bldg."
rating, 0.5% to 99.5%"			windows and R-65 roof

By this temperature-range measure there has indeed been a quality loss for the edge and corner apartments on winter resilience. A related observation is that for the DOE apartment the peak heating load by Wufi Passive static calculation was more than twice that of the building as a whole, and for the West Lake apartment it was 1.5 times the whole building peak load.

For the West Lake Tower edge apartment, because of the large glass area, the window performance appeared to be the best improvement opportunity. Changing the windows from R-4.5 to R-7.0 improved the resilience range to 39-89 F. A case was also run with phase-change drywall – it had no effect on the resilience range, but the unit did spend slightly more time near the 73 F phase-change temperature.

For the DOE hi-rise corner apartment, the improvement opportunities appeared to be the roof and window R-values, but upgrading the roof from R-26 to R-65 only raised the range to 32-86 F, and improving the windows in addition from R-3.1 to R-7 gave a range of 34-87 F. It is not entirely clear why the DOE corner apartment is scoring worse than the West Lake even after upgrades.

One thing that did become clear is that the 10-year simulation with random outages does not give as repeatable results as one would like. For the DOE apartment four re-randomizations were done and resulted in 0.5% temperature levels of 30.6, 26.6, 32.4, and 31.1 F. Although outages were not allowed to overlap, they were programmed to happen about 20 times a year and thus could occur in quick succession. Because the mechanical systems were sized for the low regular design loads, they sometimes did not have time to fully recover before the next outage. Going forward it may be a better procedure to first analyze a ten-year weather file for the coldest and hottest five days or so, and then simulate only those periods under outage conditions – what might be called a "resilience design week" approach. A related thought is that it may not be very realistic to model the probability of an outage as constant with time – more likely the probability is highest during extreme weather.

With regard to an acceptable range for this kind of metric, on the cold end, history shows that people can survive quite a lot of cold. For buildings with water pipes however, outright freezing is definitely to be avoided. At this time our sense is that 40-90 F may be an appropriate goal for such a "thermal resilience range", but it would be better to have a more scientific basis for the upper end of the range.

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