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Le Corbusier's Cité de Refuge: historical & technological performance of the *air exacte*

L.M. Diaz, R. Southall

School of Arts, Design and Media, University of Brighton

Abstract: Despite a number of attempts by Le Corbusier to implement the combination of 'respiration exacte' with the 'mur neutralisant' he was never able to test the viability of his environmental concepts in a realised building. The Cité de Refuge, which was built with a more conventional heating system and single glazed facade, is however unique in that unlike the other potential candidates for the implementation of these systems, the building, as built, retained a key design feature, i.e. the hermetically sealed skin, which ultimately contributed to the building's now infamous failure. It is commonly argued that Le Corbusier, however, abandoned these comprehensive technical solutions in favour of a more passive approach, but it is less well understood to what extent technical failures influenced this shift. If these failures were one of the drivers for this change, how the building may have performed with the 'respiration exacte' and 'mur neutralisant' systems becomes of interest. Indeed, how their performance may have been improved with Le Corbusier's later modification of a brise-soleil offers an alternative hypothetical narrative for his relationship to technical and passive design methodologies.

Keywords: environment, technology, performance, history, Cité de Refuge.

1. Introduction

There are two technical building concepts that represent, perhaps more than any others Le Corbusier's early drive to find comprehensive and exclusively mechanical approaches to the heating and ventilation of modern buildings: a) the *mur neutralisant*, a double-skin glazed wall with conditioned air circulated within the cavity to moderate heat exchange between the interior and exterior, and b) the *respiration exacte*, a mechanical ventilation system for providing conditioned air to interior spaces at a constant temperature of 18°C. The two are complementary and often considered in terms of one combined system; *air exacte*.

The *mur neutralisant* was very much Le Corbusier's concept, and as early as 1916 he developed a forerunner for the Villa Schwob, La Chaux-de-Fonds, featuring heating ducts placed at the bottom of a double glazed cavity to create a thermal barrier¹. It was not, however, until 1927 that Le Corbusier had the opportunity to engage with complex glazing again, but did so with two separate projects. The house in Stuttgart, built for the *weissenhofsiedlung* housing exhibition, featured a double-skinned glazing system, although there is no evidence of the cavity being mechanically treated (a number of Le Corbusier's drawings show the cavity being used for planting rather than active environmental control²). The second project was for the League of Nations competition entry (unbuilt) which proposed a double-skinned glazing system designed in collaboration with Gustave Lyon.

¹ Urbano Gutierrez, Rosa. "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)," *International Journal of the Construction History Society*, no. 27. Cambridge, 2012. p.109.

² Brooks, H. Allen. (ed.), *Le Corbusier Archive*, 32 vols. New York: Garland Publishing - Paris: Fondation Le Corbusier, 1982.

Lyon would develop this into an air conditioning system (*'a ration ponctuelle'*) for the Salle Pleyel in Paris (1927)³, which Le Corbusier then adopted as the *respiration exacte* system. A further collaboration between the two on the design of the Centrosoyus building (1928)⁴ eventually gave rise to the first proposed combination of *mur neutralisant* and *respiration exacte* (or *air exact*). Although the Centrosoyus project was eventually built with a double-skin façade, it was not mechanically ventilated, and the *respiration exacte* was omitted. Another opportunity to incorporate both systems came in 1931, again in the Soviet Union, with the competition for the Palace of the Soviets (unbuilt).



1. Cité de Refuge after completion ©FLC-ADAGP

The Cité de Refuge, completed in December 1933, was Le Corbusier's last significant attempt to implement both systems⁵. Due to financial constraints the building was eventually constructed with a single layer *pan de verre* (fully glazed curtain wall) instead of a *mur neutralisant*, with the *respiration exacte* relegated to a simple air heating system. Crucially, one feature was maintained due to high levels of pollution; the hermetically sealed skin. Almost immediately, complaints started to emerge of poor indoor air quality, and in the following summer of very high internal air temperatures, that eventually marked the building out as an early and notable building physics failure. The building was eventually retro-fitted with a passive external shading device, a *brise-soleil*, in 1952.

³ Ramirez-Balas, C.; Suarez, R.; Sendra, J.J. "Future Technologies in Le Corbusier's Environmental Conditioning Systems: City of Refuge in Paris," *Sustainably Architecture for a Renewable Future*, PLEA2013 - 29th Conference, Munich, 10-12 September 2013; Urbano Gutierrez, "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)," p. 109.

⁴ Urbano Gutierrez. "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)."

⁵ After the Cité de Refuge, Le Corbusier continued to propose the *mur neutralisant* when he could (Immeuble Locatif and Immeuble Rentenanstalt, both in Zurich). Ibid. p. 123.

The building's reception has oscillated between relative obscurity in the oeuvre of Le Corbusier and notoriety for its technical failure. Kenneth Frampton⁶ and Vincent Scully⁷ make no mention of the building in their histories of modern architecture while Manfredo Tafuri⁸ ignores the technical aspects of the building in his history of modern architecture. William Curtis' acknowledgement is fleeting: "...the new solution [fully glazed curtain wall] brought its own problems: lack of privacy, leaks, heat loss, and heat gain"⁹.

Other academic studies have tended to be straightforward in their declaration of the Cité de Refuge façade's failure. Yet, it is often tempered by reference to Le Corbusier's invention of the *brise-soleil* as a solution to its solar heat gain problems¹⁰. This cause-effect scenario, where the failure of a technical approach inspired a turn to vernacular and primitive technologies has become a common trope in explaining the change between the early and late modernist work of Le Corbusier, particularly among historians. Stanislaus von Moos, for example, writes:

*"After his brief enthusiasm for 'international scientific techniques' as premises of a truly international architecture, he seems to have quickly returned to the more elementary techniques of environmental control..."*¹¹

This narrative has been repeated by Curtis¹² and others¹³ and has only recently been challenged. Rosa Urbano Gutierrez suggests a more subtle interpretation arguing that while Le Corbusier adjusted his approach it was not an abandonment of, or loss of faith in, technology¹⁴. Although there is an obvious difference between Le Corbusier's early designs and his later work, the change-over was not as dramatic as is often suggested. His designs in the 'purist' and technologically centred vein (Centrosoyus, 1928; Immeuble Clarté, 1930; Cité de Refuge, 1929; Nungesser-et-Coli, 1931) overlapped with projects that utilised stone, vaults and other traditional building techniques (Maisons Loucher, stone walls, 1929; Villa in Carthage, overhanging floor plates for shading, 1928; Pavillon Suisse, curved stone wall, 1930; House in Le Mathes, stone walls, 1935). This suggests a plausible scenario where Le Corbusier might have combined his early interest in *l'air exact* with his later *brise-soleil*.

Although the Cité de Refuge's façade system, as built, failed, it is the complaints and the ensuing, well-documented¹⁵ controversy, which in part makes the Cité de Refuge such a suitable candidate for performance analysis. Anecdotal and measured data generated at the time in the tussle between Le Corbusier and the Salvation Army provide the essential information concerning the original performance of the building required

⁶ Frampton, Kenneth. *Modern Architecture: A Critical History*, 3rd ed. London: Thames & Hudson, 1992.

⁷ Scully Jr., Vincent. *Modern Architecture*, New York: G. Braziller, 1961.

⁸ Tafuri, Manfredo. *Modern Architecture*, 2 vols. Milan: Electa, 1976.

⁹ Curtis, William. *Modern Architecture since 1900*, New Jersey: Prentice-Hall, 1983, p. 203.

¹⁰ See for example: Butera, F.M. "Glass Architecture: Is It Sustainable?," in *Passive and Low Energy Cooling for the Built Environment*, Santorini, 2005, pp. 161–68; Arnold, David. "The Evolution of Modern Office Buildings and Air Conditioning," *ASHRAE Journal*, Atlanta, June 1999, pp. 40–54; Requena Ruiz, Ignacio. "An Approach to Environment and Modernity Through Le Corbusier's Drawing," *Revista de EGA*, Valencia, no. 20, October 2012, p. 246.

¹¹ Von Moos, Stanislaus. *Le Corbusier, Elements of a Synthesis*, Cambridge, Mass.: MIT Press, 1979, p. 93.

¹² Curtis, William. *Le Corbusier*, New York: Rizzoli, 1986, p. 208.

¹³ See for example, Sobin, Harris. "From l'Air Exact to l'Aérateur: Ventilation and Its Evolution in the Architectural Work of Le Corbusier," in *The Green Braid*, London: Routledge, 2007, pp. 140–52; Walden, Russell (ed.). *The Open Hand: Essays on Le Corbusier*, Cambridge: M.I.T. Press, 1977; Winter, John. "Le Corbusier's Technological Dilemma," in *The Open Hand*, pp. 322–47.

¹⁴ Urbano Gutierrez. "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)," pp. 124–25.

¹⁵ Taylor, Brian Brace. *Le Corbusier, The City of Refuge, Paris 1929/33*, Chicago - London: University of Chicago Press, 1987, chap. 4.

for the validation of a simulation model. This data, coupled with existing documentation regarding the proposed *air exact* system and the eventual installation of a *brise-soleil*, makes the Cité de Refuge the perfect template to investigate this building's failure, but also to analyse the potential performance of Le Corbusier's intended ideal and of a hypothetical version combining technical and passive aspects of his design thinking.

Three simulation models (as built, as intended, as a hypothetical combination of systems) have been used to generate data concerning the environmental and energy performance of the three scenarios. The first model is used to both verify the simulation approach and establish a benchmark. The second model provides us with a snapshot of how Le Corbusier's original conception would have performed. The speculative aspect of the third model will allow us to understand the combined effects and importance of Le Corbusier's varied experiments. In total, this examination will suggest an alternative narrative concerning Le Corbusier's perceived abandonment of technology in favour of more primitive and vernacular models for environmental control.

2. Methodology

2.1 Simulation methodology

The free and open-source EnergyPlus¹⁶ building performance simulation tool is used here to simulate the thermal and ventilation performance of the Cité de Refuge. EnergyPlus is a well validated and comprehensive tool capable of simulating complex construction and mechanical ventilation regimes. EnergyPlus itself does not have a user interface for the construction and specification of a building model so a software tool developed in-house, called the VI-Suite (<http://arts.brighton.ac.uk/projects/vi-suite>), has been used. The VI-Suite functions as a plugin for the 3D content creation suite Blender, which allows EnergyPlus geometry import/creation and the specification of construction and ventilation elements. Once the building has been characterised, the VI-Suite runs EnergyPlus and exports the results for plotting and analysis. The geometry for the Cité de Refuge was initially created in Auto CAD from detailed plans and sections of the completed building¹⁷ before being imported into Blender.

2.2 Cité de Refuge as built

The construction of the realised single glazed facades has been well documented, consisting of toughened glass with a thickness of 7mm¹⁸. This glass has been used for all glazed sections of the Southerly, Easterly and Northerly facades. Floors and internal walls have also been well documented and modelled accordingly.

The insulating walls, situated on the North, East and West facades, were installed to protect the building from the cold winter Northerly winds, and were reported to be constructed from an outer 110mm layer of terracotta brick, followed by a 20mm air gap and 50mm of internal pressed straw insulation¹⁹. Although the exact nature of the straw panels is not known, contemporary reports suggesting the wall had the same thermal insulation as a 1m

¹⁶ Crawley, Drury B, et al. "EnergyPlus: Energy Simulation Program," *ASHRAE Journal* 42, Atlanta, no. 4, April 2000 pp. 49–56.

¹⁷ Taylor. *The City of Refuge*, Appendix.

¹⁸ Ramirez-Balas, Suarez, and Sendra. "Future Technologies in Le Corbusier's Environmental Conditioning Systems: City of Refuge in Paris," n.p.

¹⁹ Taylor. *The City of Refuge*, p. 82.

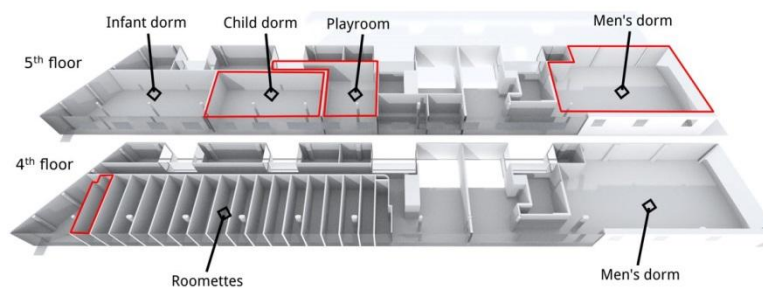
thickness of stone wall²⁰ made it possible to deduce that their thermal performance is similar to Stramit compressed straw panels which were released onto the market in 1933.

Le Corbusier was aware that a large glazed facade such as the one realised in the Cité de Refuge, which did not incorporate the *mur neutralisant*, would require shading to reduce solar heat gains²¹. In the Cité de Refuge user-configurable screens were installed on the inside of the facade. They are assumed here to have a solar reflectivity of 60%, corresponding to the off-white colour seen in contemporary photos.

In terms of ventilation and heating, the solution used consisted of a relatively simple steam boiler-based heating system that delivered heated air in winter, and supplied untreated air brought down from roof level in summer. The smaller individual rooms were ventilated with vents above the door supplied in turn by ceiling conduits in the corridors. Air left the rooms under the door and was extracted through plumbing pipes and vents placed at strategic points. Larger rooms were supplied by blowers at critical points within the building. The ventilation capacity was reported to be 1 air change per hour (ACH) in winter and 2 - 3.5 in summer, figures very much in line with modern conceptions of ventilation. Originally the ventilation system was to have eight independently controlled zones, but only four were ultimately installed due to cost overruns on the foundations²². It is not known which portions of the building were serviced by each of these four independent systems.

2.3 EnergyPlus models

The existence of contemporary reports of occupant dissatisfaction in the Cité de Refuge are extremely useful data for a building performance simulation, as they provide validation data and guidance. These reports centred on the mother & baby roomettes on the 4th floor and the playroom and child's dormitory of the child care centre on the 5th floor. All three zones have a strong relationship with the main, southerly facing, single glazed facade. The men's dormitory on the 5th floor has also been modelled due to its high occupancy and weak relationship with the main glazed facade to provide some contrast. The modelled zones, within the context of the 4th and 5th floors, are shown in figure 2.



2. Overview of the modelled zones (highlighted in red). Source: Ryan Southall.

²⁰ Ibid.

²¹ Ramirez-Balas, Suarez, and Sendra. "Future Technologies in Le Corbusier's Environmental Conditioning Systems: City of Refuge in Paris," n.p.

²² Fernandez, Vanessa; Gallo, Emmanuelle. "A Factory for Well-Bing: Innovations in the Heating System and the Curtain-Wall in Le Corbusier's Salvation Army's City of Refuge," *Proceedings of the 11th DOCOMOMO International Conference*, Mexico City, 20-25 August 2010, n.p.

After the zones of interest have been identified, the occupancy levels need to be determined for these spaces to understand the influence they will have on internal temperatures and internal CO₂ levels. Plans of the completed Cité de Refuge building clearly indicate the number of beds in each of the dormitory zones, and these beds have been used to determine the maximum occupancy for each of these spaces. The play room was designed for a maximum occupancy of 60²³. It is rather unlikely however that this level would have been reached on a consistent basis as the floor area of the space is only 52m², so maximum occupancy equivalent to the neighbouring dormitory space (31) has been used here. These occupancy levels, along with the assumed occupied periods and occupant metabolic rate in Watts per person (which defines occupant internal heat gains and CO₂ production) are shown in table 1.

Space	Occupant number (max)	Period	Metabolic rate (Wpp)
Men's dorm	35	22:00 - 08:00	90
Roomette	1	22:00 - 08:00	80
Play room	31	08:00 - 20:00	66
Child's dorm	31	20:00 - 08:00	57

Table 1. Occupancy Parameters. Source: Ryan Southall.

As some important variables relating to the operation of the building are not known, an initial modelling phase was used to confirm some of the anecdotal data that is available for certain key areas of the building.

For example, contemporary complaints suggested that the ventilation system was turned off at night, and measurements taken at the time showed that CO₂ levels in the 4th floor roomette reached 2720 parts per million (ppm). Le Corbusier responded that these rooms were receiving 35m³/hr in winter and 80 in summer. With this data, and by adjusting the period of ventilation provision within the model, it was possible to replicate these peak CO₂ levels (simulated 2700ppm) with a ventilation system in operation from 6am to 11pm.

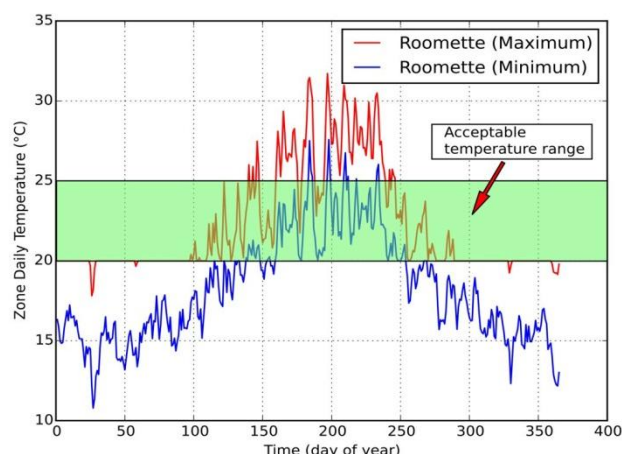
Applying this ventilation regime to the large men's dormitory on the 5th floor results in peak CO₂ levels of around 10,000 ppm. Although not dangerous these levels would definitely support the reports of extremely poor air quality and stuffiness. For the as-built case the ventilation regime has subsequently been assumed to be in operation from 6am to 11pm.

3. Results

3.1 Cité de Refuge as built (1933)

The daily maximum and minimum temperatures for one of the 4th floor mother & baby roomettes are shown in figure 3.

²³ Taylor. *The City of Refuge*, p. 98.



3. Mother & baby roomette temperatures. Source: Ryan Southall.

It is clear from figure 3 that the space does not provide acceptable indoor temperatures. Maximum and minimum daily temperatures only fall within the desired temperature range in the spring and autumn. Minimum winter temperatures regularly fall below 20°C (minimum 11°C) and summer temperatures regularly peak well above 25°C (maximum 32°C). Cooler temperatures in a dormitory space such as this one are not necessarily an issue as occupants are generally in bed, but a minimum of 11°C is too low even in this context. Modelling the shading screens inside the facade as fully closed, summer temperatures still peak at 27°C, and a combination of these two scenarios support the contemporary reports of temperatures peaking above 28°C²⁴. Table 2 shows a breakdown of the thermal performance of the modelled zones.

Space	% hours < 20°C	% occ hours < 20°C	% hours > 25°C	% occ. hours > 25°C	Peak °C
Men's dorm	9	21	20	24	30
Roomette	62	65	12 (2)	11 (2)	32 (27)
Play room	17	0	30 (15)	37 (24)	37 (32)
Child's dorm	7	14	30 (14)	33 (17)	40 (32)

Table 2. Zone thermal performance (results with shading in brackets). Source: Ryan Southall.

It is clear from table 2 that all zones experience serious thermal issues. Both the play room and the children's dorm experience peak temperatures of 32°C even with the shading screens fully deployed (this corresponds with contemporary reports of temperatures in these spaces reaching 30-33°C). Both these spaces spend approximately a third of the occupied hours below 20°C, and a third above 25°C, leaving only the remaining third as comfortable. The roomette is predominantly too cold as the heating system and low occupancy gains cannot counteract heat losses from the single glazed facade when there are no significant solar gains. The men's dorm does perform slightly better as its periphery is not dominated by the single glazed *pan de verre*, and this provides an early indication of where the problems with the building lie.

From a modern building physics perspective the reasons for the thermal failure of the building is fairly self-explanatory. High solar gains coupled with no active cooling during the daytime, and high heat losses through the single glazed facade coupled with no heating during the night-time, result in extremes of temperature that often fall outside acceptable parameters. It's possible that the situation at night could have been improved if the building had had the planned eight independently controlled zones allowing the dormitory areas to be heated or ventilated at night. However, the overheating issues would have remained as the modelled ventilation system operates at the designed capacity in all spaces during the day.

²⁴ Ibid. p. 113.

From an energy consumption perspective the heating loads for the four spaces are shown in table 3. These figures only pertain to heating, as there is no active cooling employed, and does not include losses, inefficiencies or fan power, and simply represent the raw heating energy required to supply air at the reported flow rates at 18°C. Actual figures would therefore be higher than reported here. Figures are presented in terms of annual kWh consumption and the common modern metric of annual kWh consumption by floor area.

Space	Annual kWh	Annual kWh/m ²
Men's dorm	11269	78
Roomette	626	57
Play room	2561	49
Child's dorm	4820	62

Table 3. Heating Energy Requirements. Source: Ryan Southall.

The trade-off for very poor thermal performance is the energy consumption, which is modest and even rather good compared to current standards. It is interesting to note however that even with the relative efficiency of the system Le Corbusier suspected that the system was being shut off by the building operators to save energy²⁵.

It has been claimed that the thermal comfort problems exhibited by the building are a result of the *mur neutralisant* and *respiration exacte* systems not being implemented²⁶, and the responsibility for the failure of the building has been shifted from Le Corbusier to the client and their budgetary constraints. It is therefore of interest to test this assumption, and Le Corbusier's technical design intentions, with a thermo-physical model that incorporates both these systems.

3.2 Cité de Refuge as envisioned with *mur neutralisant* and *respiration exacte*

For this new analysis, the majority of the building simulation model remains the same as in the previous section. The only changes made are to the ventilation system (*respiration exacte*) and the facade (*mur neutralisant*).

The *respiration exacte* system developed and patented by Gustav Lyon as *aeration ponctuelle* and adopted by Le Corbusier was, in effect, an air-conditioning system that supplied the occupied areas with a constant ventilation flow rate delivered at 18°C. Lyon's choice of a slightly lower temperature than would normally be considered comfortable i.e. 20°C, suggests that he appreciated that internal occupancy and solar heat gains would make up the difference, and this was explicitly noted by Le Corbusier²⁷. A noteworthy characteristic of Lyon's system was the very low flow rate supplied; 80 litres/minute/person, which equates to only 1.3 litres/second/person (lsp). This is far lower than typical modern standards of 8-10 lsp, which are designed to remove smells and moisture as well as providing a breathable environment. This flow rate was however predicated on the idea that the supply air would be heavily oxygenated by using ozone, a dubious proposition especially now that ozone has been identified as a health hazard.

²⁵ Gallo, Emmanuelle. "The Importance of Introducing the Study of Original Technical Devices in the 20th Century Architectural Heritage, for a Well-Reasoned Conservation Approach," *International Conference Intervention Approaches for the 20th Century Architectural Heritage*, Madrid, 14-16 June 2011, p. 3.

²⁶ See for example: Fernandez and Gallo. "A Factory for Well-Bing: Innovations in the Heating System and the Curtain-Wall in Le Corbusier's Salvation Army's City of Refuge"; Taylor, *The City of Refuge*; Jordan, Robert Furneaux. *Le Corbusier*, 1st Ed. New York: Lawrence Hill & Co., 1972; Sobin, "From l'Air Exact to l'Aerateur: Ventilation and Its Evolution in the Architectural Work of Le Corbusier."

²⁷ Taylor. *The City of Refuge*, p. 20.

Le Corbusier had, however, already received information that these flow rates were too low, and indeed that the use of ozone constituted a health risk²⁸. In an attempt to convince the clients for a previous project - Centrosoyus - of the efficacy of the system, Le Corbusier commissioned a report by the American Blower Company (ABC) to validate the approach. The report was however not very supportive, explicitly warning about the use of ozone and criticising the low flow rate and recommended a flow rate of 10 times²⁹ that proposed, i.e. 13 l/s, to maintain internal air quality in this type of program, figures much more in line with modern ideas of ventilation. A second report by ABC was also commissioned by Le Corbusier for the Cité de Refuge, but no record of the contents of this report exist, perhaps reflecting their negative attitude once again to the formulation of the system.

The *mur neutralisant* facade, as originally conceived by Le Corbusier, consisted of two single skins of glass between which was circulated conditioned air. This conditioned air would in theory moderate the temperature of the inner skin of glass, improving thermal comfort within the neighbouring room, reducing heat losses from the room to the outside on cold days, and reducing heat gain through the facade on hot days. Statements made by Le Corbusier indicate that he also considered the system to be able to deal with solar heat gains³⁰. Although a *mur neutralisant* was never built, testing conducted by Le Braz, and overseen by Gustav Lyon, at the Saint-Gobain laboratories³¹, in preparation for the Cité de Refuge do offer some clues into the detailed operation of the system, and plans drawn up for the Centrosoyus project offer some insight into its form. In the tests Le Braz circulated up to 150 l/s of air at a temperature of 15°C for summer operation and 30°C for winter operation through a glazed facade section 1.34m in width and with cavities of various depths. The preparatory work for the Centrosoyus building indicated an all glass *mur neutralisant* with an internal 2.5mm layer of frosted glass, a 200mm air cavity with a 9mm clear external glass layer. The cavity width is supported by Le Braz who concluded that the air cavity should be larger than 100mm to reduce the air speeds within it.

There are two obvious problems with this version of the *mur neutralisant*: two clear glazing layers do not significantly reduce solar heat gain, and circulating conditioned air within a cavity only separated from the outside by a single pane of glass will incur significant heat losses in winter - a point also made in the earlier report by ABC. Le Braz made some recommendations to address these weaknesses. He suggested an extra pane of glass on the outside of the ventilated layer to reduce heat losses to the outside³² and even suggested an external shading device to reduce solar gains, although the concept of the *brise-soleil* as such did not yet exist.

The *air exact* system as originally envisaged by Le Corbusier and Gustav Lyon would not only have delivered harmful ozone into the building but when simulated demonstrated thermal performance even worse than that seen in the as-built case. Subsequent analyses in this section therefore incorporate the recommendations made by Le Braz (a third layer of façade glazing) and ABC (increase in *respiration exacte* flow rate). The parameters used in the EnergyPlus model are therefore:

²⁸ Urbano Gutierrez, Rosa. "Le Pan de Verre Scientifique: Le Corbusier and the Saint-Gobain Glass Laboratory Experiments (1931-1932)," *Architectural Research Quarterly* 17, no. 1, Cambridge, 2013, n.p.

²⁹ Urbano Gutierrez. "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)," p. 115.

³⁰ Le Corbusier; Boesiger, Willy. *Le Corbusier: Oeuvre Complet 1938-1946*, vol. 4, Zurich: Editions d'Architecture, 1977, p. 115.

³¹ Urbano Gutierrez. "Le Pan de Verre Scientifique: Le Corbusier and the Saint-Gobain Glass Laboratory Experiments (1931-1932)."

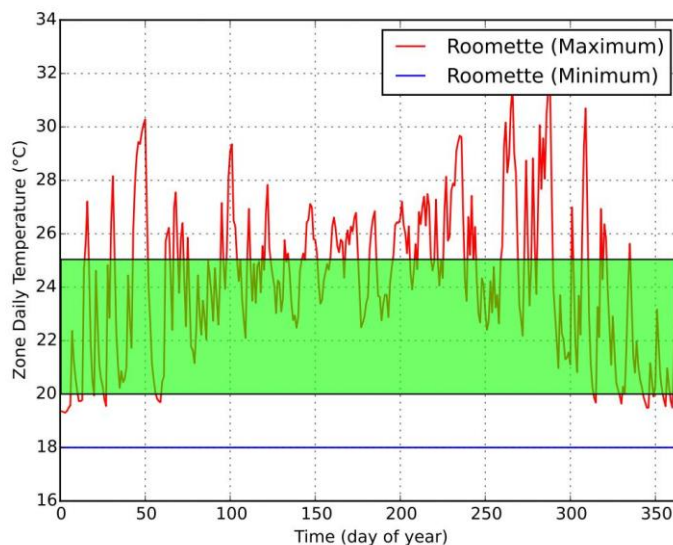
³² *Ibid.* p. 68.

- The ventilation rate of the *respiration exacte* has been set to 13 lsp based on the maximum occupancy of the space.
- *respiration exacte* supply temperature is a constant 18°C
- The construction of the *mur neutralisant* is 2.5mm internal glass layer with a 200mm ventilated cavity, 2.5mm glass layer, 14mm closed air gap and 9mm external glass layer.
- The ventilation rate within the *mur neutralisant* is up to 150/1.34 l/s per metre of facade section to match the rate used in Le Braz's testing.
- The temperature of the air supply to the *mur neutralisant* is 30°C in winter, 15°C in summer and supplied up to the maximum flow rate to maintain a cavity temperature of 18°C.

It should be noted that at 13 lsp there were no simulated air quality issues (in terms of CO₂ concentration) in any of the modelled spaces, and for brevity these results have not been included here.

3.2.1 Simulation Results

Daily maximum and minimum temperatures for a 4th floor mother & baby roomette are shown in figure 4.



4. Roomette temperatures with *air exact*. Source: Ryan Southall.

As the rooms are heavily exposed to the glazed facade, and the flow rate of the moderating *respiration exacte* is low due to the low occupancy, the rooms still suffer from significant overheating issues with peak temperatures still reaching 31°C. The three glazing layers and the moderated temperature of the *mur neutralisant* do however reduce heat losses to the outside and temperatures do not go below the *respiration exacte* supply temperature of 18°C. This lower temperature is unlikely however to have generated significant user complaint as occupants are in bed at night and indeed temperatures slightly below 20°C may, in this context, be considered perfectly acceptable.

Temperatures within the other zones exhibit reduced peak temperatures as the greater occupancy means greater *respiration exacte* flow rates, and no other zone now experiences any significant period of time above 25°C. The children's dorm does see peak temperatures of 27°C, albeit rarely and not during the occupied hours. It is a

testament to ABC and the greater American experience of air-conditioning at the time that the flow rates recommended by them are generally able to provide comfortable conditions and, with the exception of the roomettes, keep upper temperatures within the desired range.

The men's dorm does see significant occupied time with minimum temperatures below 20°C but as once again the occupants are generally in bed, and the lowest temperature exhibited by the space is 17°C, this is unlikely to cause major discomfort.

A summary of the thermal performance of the modelled zones is shown in table 4.

Space	% hours < 20C	% occ hours < 20C	% hours > 25C	% occ. hours > 25C	Peak
Men's dorm	65	58	0	0	24
Roomette	13	12	18	10	32
Play room	25	0	0	0	25
Child's dorm	9	0	1	0	27

Table 4. *air exact* zone thermal performance. Source: Ryan Southall.

In summary, the thermal performance of the *air exact* system would have been much improved compared to the as-built case if the recommendations of Le Braz and ABC had been implemented. The energy consumption figures do however tell a very different story. Total energy consumption for heating and cooling are shown in table 5. These figures, where appropriate, also include the heating/cooling consumption of the *mur neutralisant* associated with a particular space.

Space	Annual kWh	Annual kWh/m ²	% change
Men's dorm	9805	68	-13
Roomette	2319	211	370
Play room	13236	254	518
Child's dorm	22277	284	458

Table 5. *air exact* heating/cooling energy requirement. Source: Ryan Southall.

Energy requirements have increased significantly with the exception of the men's dormitory, which is not heavily exposed to the *mur neutralisant*. The roomette, play room and children's dorm do however experience energy consumption increases of 370%, 518% and 458% respectively, which is the trade-off for better thermal comfort performance in these spaces.

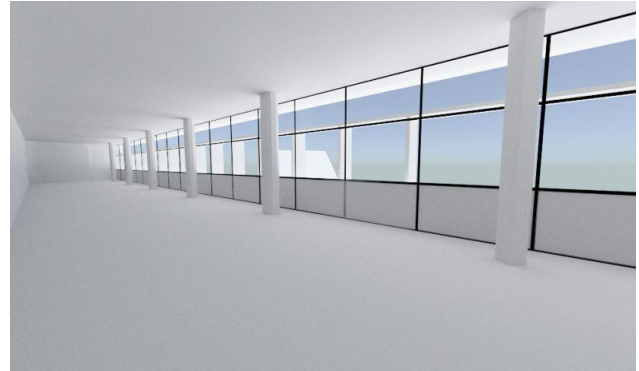
It's maybe worth considering the context within which ABC made the recommendations in their report. At the time, air-conditioning in the US was largely considered for heavily glazed commercial developments underwritten by wealthy clients. The Cité de Refuge, run and operated by a charity, represents a very different client and if Le Corbusier was correct in his suspicion that the Salvation Army were turning off the implemented system to save money, it is safe to say that the energy consumption figures presented here for the *air exact* would have caused quite some concern. It does seem quite possible that if the *air exact* system had been realised complaints from the building owner would still have occurred, and although still fundamentally in part a result of high solar gains (85% of the energy consumption figures above are required for cooling), the bulk of these complaints would have focused on energy consumption rather than thermal comfort and air quality.

Considering that in the period between the construction of the Cité de Refuge and the post-war retro-fit of the *brise-soleil* Le Corbusier was toying with the idea of combining the *brise-soleil* and *mur neutralisant*³³, and that complaints from the building owner could still have been generated by high solar gains, it is conceivable that Le

³³ Ibid. n.p.



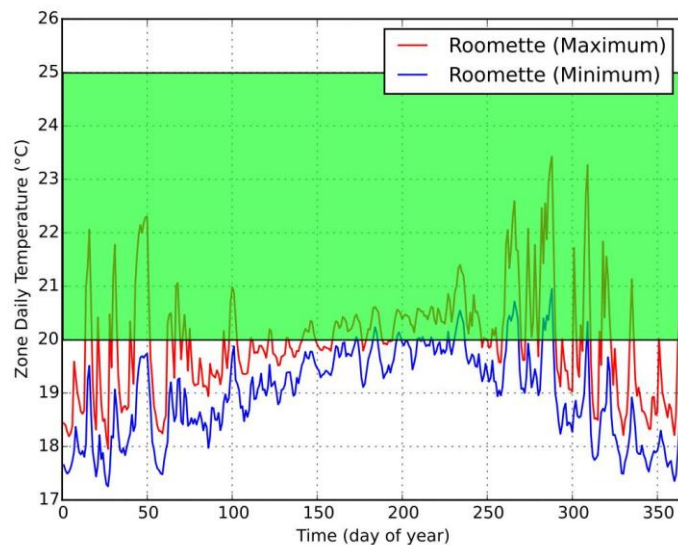
6. Cité de Refuge with *brise-soleil*.
Source: Luis Diaz



7. Rendering of internal illumination on 5th floor.
Source: Ryan Southall.

3.3.1 Simulation Results

The daily minimum and maximum temperatures of the roomette are shown in figure 8 and present a very different picture to the previous analyses. Overheating has now been completely eliminated and minimum temperatures, at over 17°C, would be unlikely to cause problems for sleeping occupants.



8. Roomette temperatures with *brise-soleil*. Source: Ryan Southall.

The thermal results are summarised in table 6. Of note is that fact that none of the spaces now see any overheating, either in the occupied or non-occupied periods. Peak temperatures are now well below the upper value of 25°C specified in Le Braz's testing, creating, in summer time, what could be considered quite a cool, pleasant environment. Also of note is the high percentage of the time that the rooms experience temperatures below the lower threshold of 20°C. Now that internal solar gains have been reduced the *respiration exacte* system supply temperature of 18°C often delivers temperatures between 18 and 20°C. In the dormitory spaces this is not of major concern as occupants are generally in bed. In the play room, where occupants are not in bed, these low

temperatures only exist for 12% of the occupied time and the absolute minimum during these times is a respectable 17°C. All things considered the thermal performance of the building can now be considered to be very good, and indeed offer some leeway in the way the building is operated. Somewhat lower *respiration exacte* flow rates would for example still not lead to overheating.

Space	% hours < 20C	% occ hours < 20C	% hours > 25C	% occ. hours > 25C	Peak
Men's dorm	65	58	0	0	24
Roomette	69	67	0	0	23
Play room	60	22	0	0	23
Child's dorm	51	12	0	0	22

Table 6. *air exact* with *brise-soleil* thermal performance. Source: Ryan Southall.

Energy consumption figures are shown in table 7 along with the percentage reduction compared to the simple *air exact* case. In the roomette, for example, the significant reduction in internal temperature has led to an energy consumption reduction of 65%, to a very reasonable 73kWh/m². In the childcare centre rooms, which have higher occupancies and higher *respiration exacte* flow rates, the consumption is higher but still 38-52% lower than without the *brise-soleil*. The absolute figures for the childcare centre are slightly high by modern energy efficiency standards but about as low as could be expected in an air-conditioned building with high occupancy levels. Further improvements could be achieved by more intelligently controlling the *respiration exacte* system in response to occupancy rates, especially as there is now some leeway in terms of peak temperatures.

Space	Annual kWh	Annual kWh/m ²	% reduction
Men's dorm	9816	68	N/A
Roomette	798	73	65
Play room	8183	157	38
Child's dorm	10814	137	52

Table 7. *respiration exacte* heating/cooling energy requirement. Source: Ryan Southall.

3.4 Conclusions

Historical accounts make a compelling case, despite Le Corbusier's protestations at the time, for considering the building as built a technical failure. The simulations confirm this verdict and replicate the poor air quality and very high internal temperatures experienced by the occupants. The failure was largely a result of the hermetically sealed skin, kept as part of the original proposal for *air exact* and motivated by Le Corbusier's drive to keep out external pollutants, and the high solar gains combined with no active cooling system.

Historians have been more ambivalent on the question of Le Corbusier's proposed system of *air exact* while some academics have been unequivocally positive about it³⁷. The very low *respiration exacte* flow rates originally proposed by Lyon would, however, have delivered performance even worse than the built version. Even when considering the improvements suggested by ABC and Le Braz, the system does not eliminate thermal problems completely, even with the significantly increased energy consumption. Both performance issues are

³⁷ Ramirez-Balas, Suarez, and Sendra. "Future Technologies in Le Corbusier's Environmental Conditioning Systems: City of Refuge in Paris," n.p. "*The City of Refuge...did not manage to convince with the innovations which he had hoped would provide a solution to temperature control problems. This was mostly due to the obstacles encountered in the building, which prevented the execution of one of the most brilliant technological innovations proposed by Le Corbusier: the combination of the mur neutralisant and the respiration exacte.*"

again in part due to the high solar heat gains, but while the approach may have been conceptually naive it was not due to a lack of awareness on Le Corbusier's part of the potential problems associated with solar gains³⁸.

If the client for the Cité de Refuge had been wealthy and less concerned with running costs, as with most clients of air-conditioning systems at the time, this hypothetical narrative could have ended there, and Le Corbusier could have carried on believing that the *air exact* system obviated the need for any external shading. It is clear however that the Salvation Army were pressed³⁹ to afford the capital investment in these technologies and it is not a stretch to suggest that it would have been crippling had they been faced with the operating costs associated with the *air exact*. Coupled with the persistent thermal issues in the roomettes, it is very possible that Le Corbusier would have found himself in a very similar situation to one he faced in reality; a very unhappy client whose dissatisfaction was partly derived from high solar heat gains. Knowing that in real life Le Corbusier recommended external shading, and bearing in mind evidence that Le Corbusier himself, in the period after the Cité was built, experimented with the idea of combining the *brise-soleil* and *mur neutralisant*⁴⁰, it is reasonable to speculate that he would also have employed a *brise-soleil* in this hypothetical Cité when the opportunity arose after the war. The simulation of this combination indicates good thermal performance at a much reduced energy cost and suggests that Le Corbusier could have realised in 1952 a combination of his active and passive technical design thinking that would have performed very well. This model not only performs at levels comparable to present standards, including in terms of energy use, but also prefigures the common use of passive shading integrated with double skin glass façades that is ubiquitous today. This combination of a mechanical ventilation system with passive solar shading also represents an imagined and hypothetical shift in Le Corbusier's work. Yet, this invented trajectory isn't far from Le Corbusier's own approach in some of his last works such as the Carpenter Center in Boston and Heidi Webber Pavilion in Zurich. In the development of Le Corbusier's attitude to the *mur neutralisant*, from a system that could eliminate the appreciated problem of solar heat gains, to one that could be used in combination with external shading one can maybe read his attitude to technology more generally; an attitude that evolves ideas rather than displaces them. As Gutierrez has argued, the perceived 'rejection of technologies' post the Cité de Refuge, oversimplifies what is a more complex history. The hypothetical Cité de Refuge can be seen to represent a compressed body of knowledge about propositions and actual constructions from which Le Corbusier drew on and which prefigures some of his later projects. This suggests an interpretation of the Cité de Refuge that sees it less as a watershed project and more as part of a continual process of thinking about architecture and its relationship to various kinds of technologies. The shift in Le Corbusier's work can be seen to revolve less around an abandonment of technology and more an evolution away from reductive and idealistic expectations placed on a single technological system. If, in 1952, he had successfully realised a combination of distinct active and passive systems it could be expected that this interpretation of the development of his technical thinking would be more prevalent today.

³⁸ Le Corbusier and Boesiger. *Le Corbusier: Oeuvre Complet 1938-1946*, vol. 4, p. 115. "The curtain wall should have been a 'neutralizing wall'. But the authorities modified the idea, installing conventional central heating with radiators, leaving pending the problem of summer sun. In its present state, the solution would be to equip the glass wall of this building with a sun-breaker!"

³⁹ Taylor. *The City of Refuge*, p. 17; Urbano Gutierrez, "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)," p. 116.

⁴⁰ For example, this was proposed for the UN Building. Urbano Gutierrez. "Pierre, Revoir Tout Le Systeme Fenetres: Le Corbusier and the Invention of the Mur Neutralisant (1928-1935)."

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