"Pierre, revoir tout le système fenêtres": Le Corbusier and the development of glazing and air-conditioning technology with the Mur Neutralisant (1928-1933)

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Abstract

Le Corbusier (1887-1965) became involved in the creation of a good number of artefacts throughout his career, many of them patented and developed in collaboration with the building industry. His mur neutralisant (1928) formed part of an extensive set of emergent propositions to integrate systems of artificial climate into architectural components. The invention appeared as an early prototype of a double-skin façade which included an air-conditioning circuit to improve comfort and energy efficiency thanks to an optimised insulating performance. The system was envisioned in any material, but it was the version that included a double-skin glass façade that it became instrumental in backing up one of his most important design elements, le pan de verre (glass curtain-wall). References to this invention repeatedly focus on a limited number of facts, providing only a partial understanding of its physical definition, performance and developmental context. In order to provide a holistic understanding of the concept of the mur neutralisant, this paper follows its development as well as the key role this element played in some of Le Corbusier's most celebrated buildings of that period.

Key words

Le Corbusier, *mur neutralisant*, *respiration exacte,* double-skin glass facades, air-conditioning.

Introduction

Although it has often been mentioned in the literature, the *mur neutralisant* ("neutralising wall") has never been properly investigated. More often than not, a cryptic sketch by Le Corbusier is used (Fig. 1), which provides its basic depiction as a double façade including a closed air-conditioning circuit, but lacks a detailed description or representation of its *modus operandi*. The unfortunate vicissitudes that surrounded the design of the glass curtain-wall for the south façade of the City of Refuge (1929-33) are often reported, even though the system in that building was never implemented. Some authors suggest that the long legal case with its ensuing penalties not only consigned the contentious system to permanent oblivion but it also marked the critical point at which Le Corbusier began generally to shy away from all those architectural elements which were based firmly on technical resources, in order to start to see in a more positive light solutions of environmental control rooted in vernacular and passive methods [1]. In other cases, the discussion around the *mur neustralisant* has been presented in relation to the *brise-soleil*, one of Le Corbusier's most well-known environmental control devices [2].

To add further confusion, the emergence of the *mur neutralisant* is also susceptible of some clarification. Although Le Corbusier indeed claimed the authorship of this device, evidence of clear precedents suggests that his role was more as a visionary interpreter with a great capacity to realise, ennoble and vehemently publicise an idea which, as Jean Pierre Traisnel has noted [3], had been around for a while. The double glass façade, in particular, originated in the seventeenth-century as the "storm window" developed in Europe, where the outer leaf was added during the months of cold and storms to provide a second protective barrier, and was removed in the summer period [4]. The added layer improved thermal insulation by warming the air trapped in the cavity by means of the glasshouse effect. Abundant studies from the eighteenth and nineteenth centuries pondered the use of the second glass layer to wrap windows and even the entire building, as a measure to avoid heat losses, considering the double window as a separate independent unit [5]. This independent character was undoubtedly one of the main features of Le Corbusier's proposal.

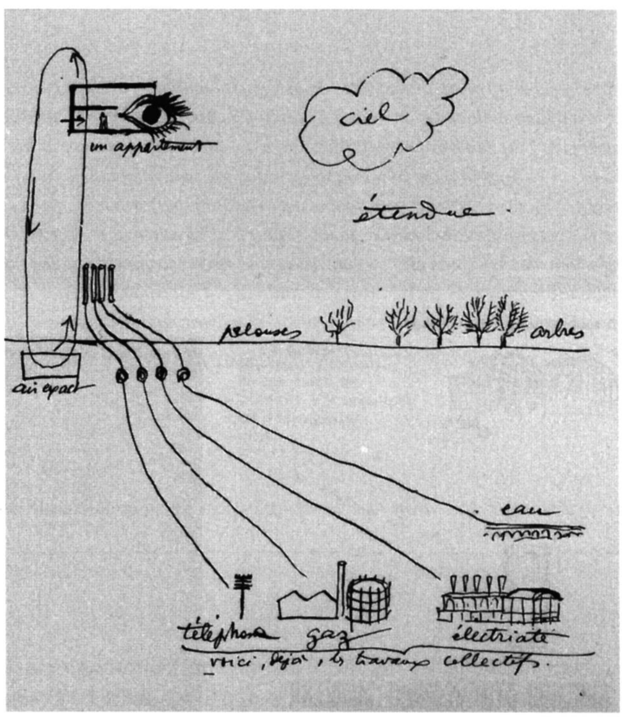

Figure 1. Le Corbusier, sketch of the air exact concept. Drawing published in La Ville radieuse (Paris: Vincent, Fréal, 1933). © FLC/ADAGP, Paris and DACS, London 2012.

The use of glass at that time was largely supported by important discoveries of the period. In particular, the hygienist theory [6] proposed the use of surface materials with certain qualities that specially favoured the use of glass - a reflective (non-porous *ergo* non-absorbing), easily-cleanable material, which also provided natural light (that, at the time, had recently been shown as a determinant factor in the eradication and cure of dangerous diseases, notably tuberculosis). From these hygienist premises, two distinct action lines strongly promoted an association between glass and social progress, which Le Corbusier followed unconditionally [7]. The first was the use of big, flat and smooth expanses of glass, in order to create bright interiors. The second was the use of glazed surfaces that are hermetically sealed to keep dust, germs or noise away from modern life. These propositions settled into two tendencies for modern architecture and the glass industry: the challenge to design and manufacture increasingly larger glass panes that reduced the numbers of joints in the glazing (considered to be the weak points regarding weather control and dirt accumulation); and the segregation between the functions of ventilation and lighting in the glass façade. These concomitant events were determining factors in the development of initial concepts leading towards the complete glass envelope.

Le Corbusier was well aware of the investigations into heating and forced ventilation technology that led to important developments during the nineteenth century, particularly in Great Britain and France. Numerous designs for walls, floors and ceilings emerged, as multi-layered assemblies with cavities that housed innovative heating, cooling and ventilation equipment of all kinds: the distribution of thermal energy using cool or hot air, water and steam; blowers, radiators, valves, registers and vents were, among other devices, part of the new set of elements that composed a building's plane surfaces. Consequently, by lodging, transporting and regulating these forms of energy, the building's skin began to acquire an active role using that cold or heat to cool or warm the double facades, either to temper the environment or to reach the desired balance between the opaque and the transparent sections of the wall. Some of these solutions were collected or advertised in Le Corbusier's own publications [8].

It is these many different aspects that compose the intriguing atmosphere around the idea of the *mur neutralisant* that triggered this study, whose ultimate goal is building up a conclusive understanding of this elusive device. To that end, this article offers a re-evaluation of the available evidence to clarify the ambitions and extent of the original conception of the *mur neutralisant.* It will describe the invention itself, as well as Le Corbusier's endeavours to apply it in some of his most paradigmatic projects of that time.

The Centrosoyus: a definite statement for a theory of respiration exacte

In October 1928, Le Corbusier made his first journey to Moscow to work on his competition entry for the construction of the Central Union of Consumer Cooperatives or Centrosoyuz Building (1928-36). From Russia, Le Corbusier wrote a note addressed to his cousin Pierre Jeanneret with whom, at the time, shared the running of his office [9]. The note is succinct but eloquent: *"Pierre, revisit the whole window system. We might perhaps use double-glazing and heat between the panes. Consult G. Lyon and laboratory. Study one hot-water heating for offices; one hot-air heating per double-glazed partition to keep out the cold"* [10].

The note mentions a figure who played a key role in the conceptual development of the *mur neutralisant*: the engineer Gustave Lyon (1857-1936). Le Corbusier had worked with Lyon since 1927, on the design of the acoustics and air-conditioning system for the eight-storey Great Assembly Hall at the League of Nations in Geneva (1927-8). During those initial designs, Lyon soon developed his own theory for optimising a ventilating system for auditoria, leading to an invention patented as "*aération ponctuelle*" [11]. This invention was based on the movement of a certain amount of air, periodically purified, tempered at a constant temperature of 18°C, and moistened, using closed circuits pumped through the double glazing by means of large mechanical fans [12]. Le Corbusier's interest in relating environmental technology and architecture had been previously explored in the two housing estates at Pessac and Lège designed for the Bordeaux industrialist Henri Frugès (1879-1974) between 1923 and 1926, for which he proposed a hot-air heating system combined with Robur stoves [13], and in the facades of Villa Schwob (1916) in la Chaux de Fonds, Switzerland. In this early experience Le Corbusier located the heating ducts at the bottom of the concrete double walls, using convection to warm the air contained in the internal cavity, raising the temperature on the surface of the perimeter walls of the house which, by radiation, would in turn warm the interior spaces. The same technique was used in the main windows of the house, including a curtain-wall spanning three storeys (Fig. 2).

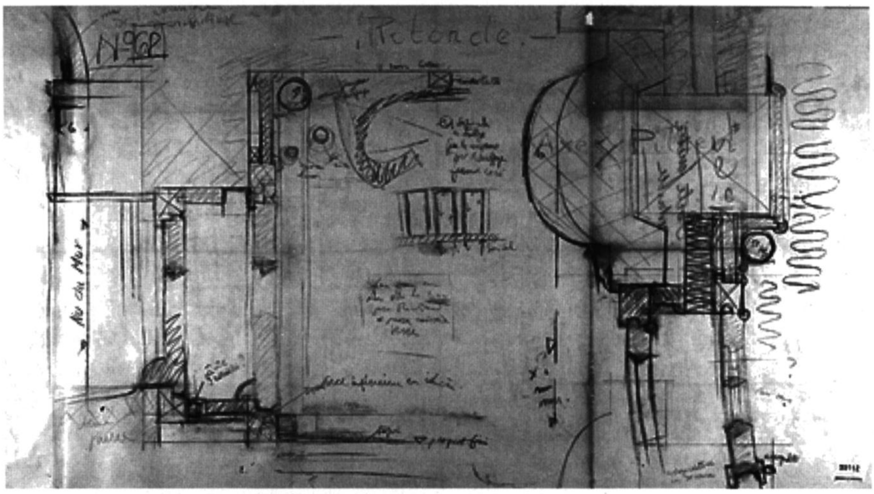

Figure 2. Le Corbusier, sketch of the double-glazing at the Villa Schwob rotonde, la Chaux-de-Fonds, 1916. FLC 30112. © FLC/ ADAGP, Paris and DACS, London 2012.

Similar techniques had previously been implemented in other buildings [14], explicitly in the double-pane glass windows fed by a hot-air circuit designed for the Winter Palace [15] in Saint Petersburg as early as 1883. However, the use of internal warm air in such a large expanse of glass does seem to have been unprecedented (Fig. 3). Le Corbusier also gave birth to a new concept when he expressed his intention in this project to achieve a "neutral" glass wall, moving away from the mainstream concept of insulation [16].

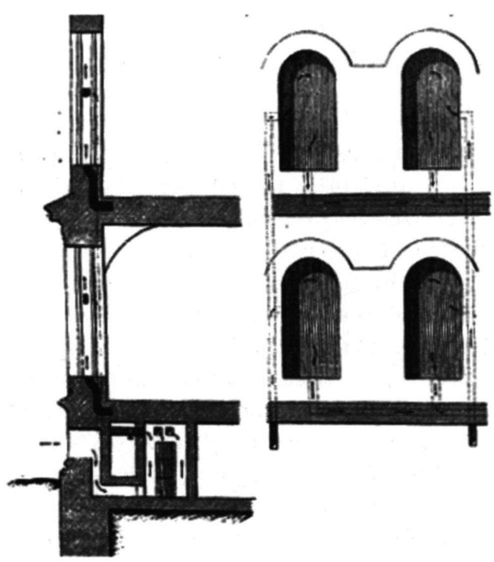

Figure 3. Hot-air heating system for warming the double-windows in the Winter Palace in Saint Petersburg, 1883. Drawing published in Nouvelles Annales de la Construction (Paris, 1883-4).

Yet, it was not until Le Corbusier returned to Paris in November 1928, when his atelier was asked to present a third revision of the Centrosoyuz project, that Le Corbusier and Jeanneret became particularly concerned with the elaboration of a holistic artificial climate strategy. This was called (in French) *respiration exacte* or *air exact* ("exact air"), from which the concept of the *mur neutralisant* was derived to supplement Lyon's ventilation system.

The principles of the *respiration exacte* theory were planned on the following basis. The fresh air was conditioned in a plant, and impelled throughout the building spaces by means of fans. The stale air was extracted and conducted back to the plant to be purified, ozonised, refreshed and warmed again to 18°C, ready to be returned to the building. That air at 18°C provided ventilation in all the rooms of the building, and was the air that the occupants would breathe at a rate of 80 litres per minute per person. The scheme did not include radiators or coolers, as it was only that treated air at 18°C that was used to provide the environmental comfort, which was the reason why the building had to be hermetically sealed to avoid any air-exchange with the exterior. To avoid the dissipation and contamination of that internal air at 18°C, the building's envelope (not only the facades but also the roof and ground floor raised on *pilotis*), housed a circuit of cold or hot air that what was called the *mur neutralisant*. To make the system adaptable to all geographical locations, the *murs neutralisants* wrapped the building with warm air when the exterior temperature was cold, and with cold air when the external temperature was hot, so that this envelope would "neutralise" the impact from the exterior and maintain the internal equilibrium intact. With this approach, each building had two conditioning plants, one to treat the air to be breathed; the second to produce the tempered air that would neutralise the building [17] (Figs 4-5).

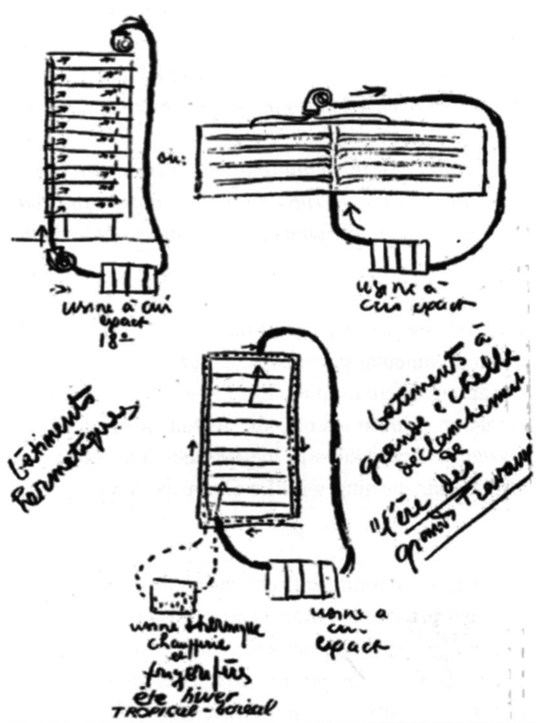

Figure 4. Respiration Exacte: sketches by Le Corbusier illustrating the two air circuits for thermal comfort and ventilation, published in Précisions (Paris: Editions Crès, 1930). © FLC/ ADAGP, Paris and DACS, London 2012.

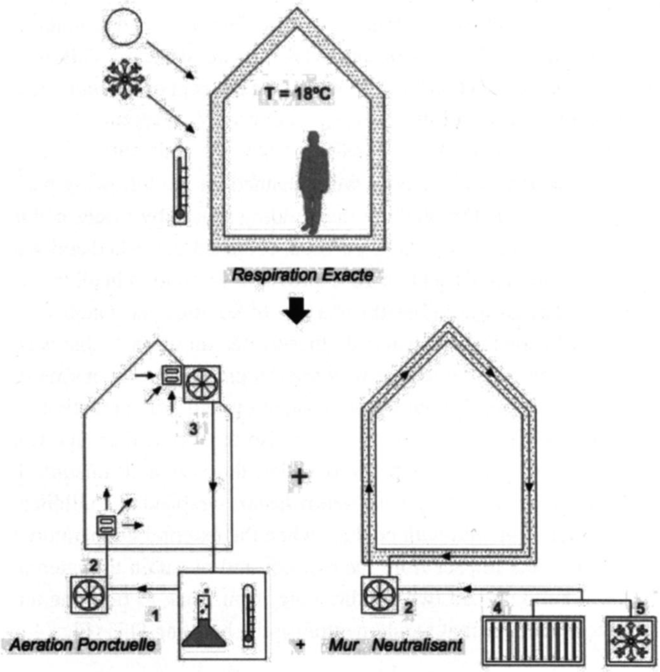

Figure 5. Conceptual diagram of the Respiration Exacte.
KEY
1. *Plant for the production of "exact air" purified and tempered at 18°C.*
2. *The "exact air" is pumped and released in all the rooms through mechanical ventilation (fans + ducts + inlets)*
3. *Stale air is extracted and returned to the plant (outlets + extraction fans + ducts).*
4. *Heating plant to feed the warm air circuit running in the cavity of the double facade in winter.*
5. *Cooling plant to feed the cold air circuit running in the cavity of the double facade in summer*

By January 1929, when the first new set of plans of the Centrosoyuz was submitted to Moscow, a large glass façade containing the environmental system held a prominent role in the presentation of the project, although only conceptual diagrams were used to describe it. There were no calculations, dimensions or any other technical information. Unfortunately, the technical challenge, the vague definition, and potential cost of such a system raised doubts in the Russian committee, whose demands for proof of feasibility became primary in their meeting with Le Corbusier's during his second trip to Moscow in June 1929 [18].

In January 1930 (one month before the imminent submission of the construction plans, and three months before the project was finally entrusted to his team), Le Corbusier sought support for the implementation of the *respiration exacte* system by consulting the American Blower Corporation (ABC), a company that manufactured ventilation and heating equipment. His letter consisted of only two pages, mostly expressing his enthusiasm for, and confidence in the invention [19], but containing scarce information about the system itself. The only documents attached were a couple of schematic perspective sketches of each circuit of the system, and a set of photographs and drawings of the Centrosoyuz building.

By analysing these early diagrams (containing only lines, arrows and icons but no dimensions), two different spatial approaches are revealed. An initial proposal shows a ventilation system based on two feed and return pipes for each of the main sections of the building, centred on its vertical axis, and covering the entire height of the block [20] (Fig. 6). On each floor, a pair of secondary ducts was also centred in each of the main sections of the building, and arranged perpendicular to the main ducts: one to supply pure air, situated at floor level, and one to extract vitiated air, situated at ceiling level. Only one extraction outlet was proposed for each floor, while the delivery of purified air was provided by a 2m x 1m grid of inlets (*aération ponctuelle*), creating a uniform and symmetric distribution of air throughout its surface [21]. The *murs neutralisants* complemented the system in an autonomous way [22], placing independent pipes at the edges of each floor, feeding and extracting air to and from the double facades of each section. In the same manner, one air inlet was at floor level, so that warm air rises and is exhausted through outlets built into the ceiling. Together this formed a series of 4m-high, single-storey systems (Fig. 7).

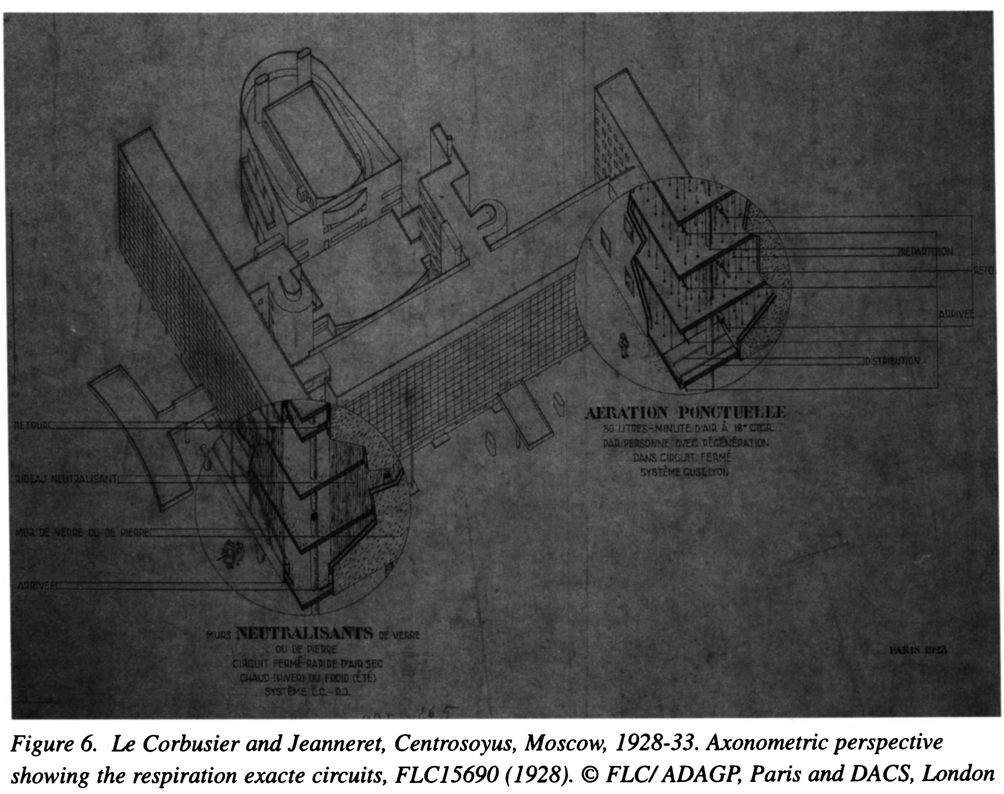

Figure 6. Le Corbusier and Jeanneret, Centrosoyus, Moscow, 1928-33. Axonometric perspective showing the respiration exacte circuits, FLC15690 (1928). © FLC/ADAGP, Paris and DACS, London 2012.

In what seems to be later drawings [23], the two systems were combined. The previous grid disappeared, reducing the feed system to a larger conduit for the whole perimeter of the building. Those sections with offices in only one façade retained one exhaust outlet in the ceiling; sections with offices in both facades incorporated three outlets, arranged symmetrically. The release of fresh air occurs at the lowest point of the façade (at floor level of the first floor) and air is collected at the highest point (at the cornice), thus forming a single system running through the entire six-storey height of the double façade (24 m), before returning to the plant. In this new scheme, the supply and collection of air within the *murs neutralisants* was planned in such a way that the air flow was no longer segmented floor by floor, but regarded as a continuous wrapping, considering the building envelope as a complete independent unit (Fig. 7). Nine days later the Americans returned a six-page report. The report offer no calculations, but described the method they had used to assess the proposal and presented their conclusions. To evaluate the system, they assessed the proposed wing of the Centrosoyuz building from different points of view including a comparative analysis in terms of heating, ventilation and cooling performances, consumption of steam and power, and both initial capital costs and running costs.

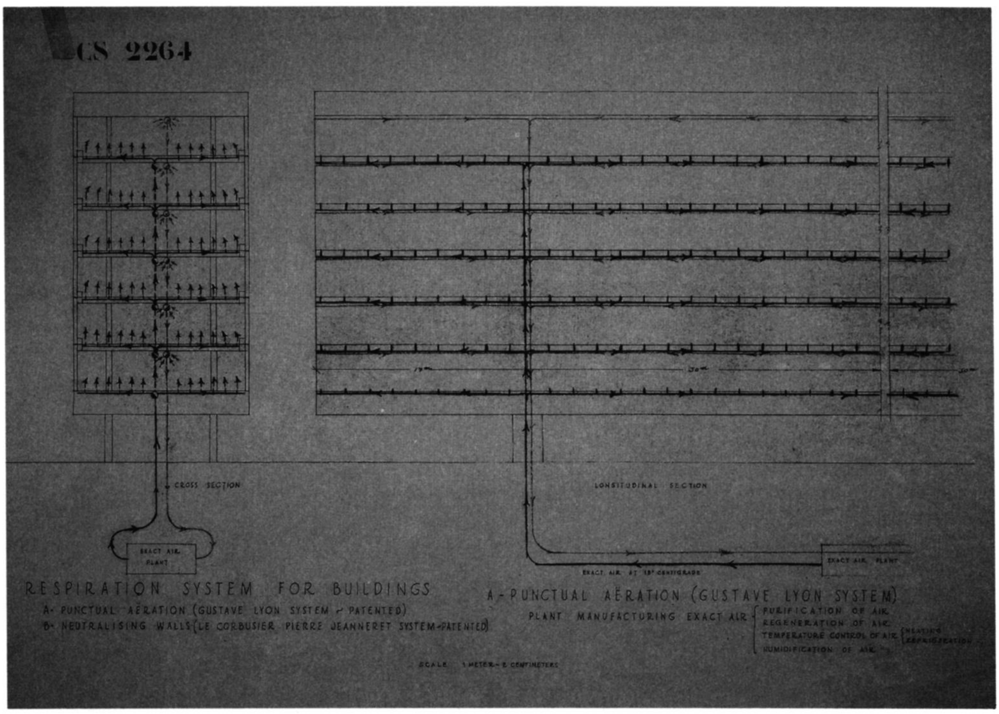

Figure 7. Le Corbusier and Jeanneret, Centrosoyuz, sections of the respiration exacte working principles, 3 January 1930. FLC 15720. © FLC/ ADAGP, Paris and DACS, London 2012.

The contents of the report could not have been more disheartening. The assessment was devastating:

> "Our hasty and somewhat superficial calculations indicate that the method proposed would require, in order to heat and ventilate the building, four times as much steam and twice mechanical power as would be necessary with methods currently employed in our country under comparable atmospheric conditions. Regarding the cooling requirement, this proposal would demand three times as much volume of air in order to make the room environmentally comfortable as would be necessary with ordinary current methods" [24].

ABC specialists explained that the bad performance stemmed from the erroneous conceptual formulation of the system itself. The greater amount of calorific energy required arose from the introduction of circulating hot air in the cavity between the two glass leaves. The heat transmission from this space through the exterior surface of the glass panel towards the exterior space was approximately three times greater than would be needed if using still air, which is a poor heat conductor, whereas air in continuous movement was continuously replaced, and effectively became an excellent conductor of heat. This meant that the temperature of the circulating air in the intermediate space must be relatively high to make up for the heat lost through glass to the exterior, and the heat transmission towards the room on the other side. That heat supplied therefore had to be, approximately, three times greater than would be required using common methods.

Concerning the ventilation system, ABC experts estimated that the amount of fresh air used to replenish the building was insufficient to ensure healthy ventilation, providing only one seventh or eighth of what they considered as the minimum necessary for auditoria, and one tenth of what they regarded as necessary for a building of this genre. Furthermore, Le Corbusier's diagrams underestimated the dimensions of the installations required, with ducts and inlets/outlets far too small to carry the necessary volume of air. ABC usually designed their installations with all the plant located on the roof, with the ducts going down through the building inside the hollow structural columns. In this way any radiation from the walls would be eliminated, thus producing complete and uniform heating.

Meanwhile, the Russian rejection of the system proposed was evident even before the arrival of the American report. Indeed, in the set of plans produced at the end of January 1930 there no sign of Corbusier's innovative proposals. Conventional radiators and a combination of roller blinds and curtains protected the double glass facades from the cold and heat. Only the double-skin glass facades remained, although they were not hermetically sealed, nor did they incorporate any innovative features. Despite being the first time the architects actually had built a glass curtain wall, and one of the first ever examples of a massive double glass façade, little attention was given to its architectonic and compositional design; it was conceived as a straightforward enlargement of a traditional, double-glazed window, up to façade scale [25].

The floor slabs were cantilevered approximately 1.25m beyond the columns along the glass façade, with their edges designed to accommodate the metalwork of the curtain wall attached to its outer face, as well as to collect condensation on the interior. Slabs edges and parapets emphasised the horizontal lines in the elevations. Between the floor slabs and structural columns, the 4m high by 6.5m long modules of glass surface were sub-divided into three equal horizontal bands by secondary structural elements made from 50mm L- and T-section steel profiles. The upper and lower bands were fixed glass sections (or concrete panels in the facades with parapets) and the central band was openable in some modules. All the fixed frames were made of steel, whereas the opening sections were made as sliding oak frames (Fig. 8). Multiple drawings provided construction details for all the facades and the different types of windows (using wired, frosted and clear glass), but nothing specific was included regarding the new concept of the "neutralising wall". The only archived document that shows a technical drawing of the *respiration exacte* plant, depicting the working principles of the air-conditioning processors, had been produced earlier on, 15 January 1930 (Fig. 9).

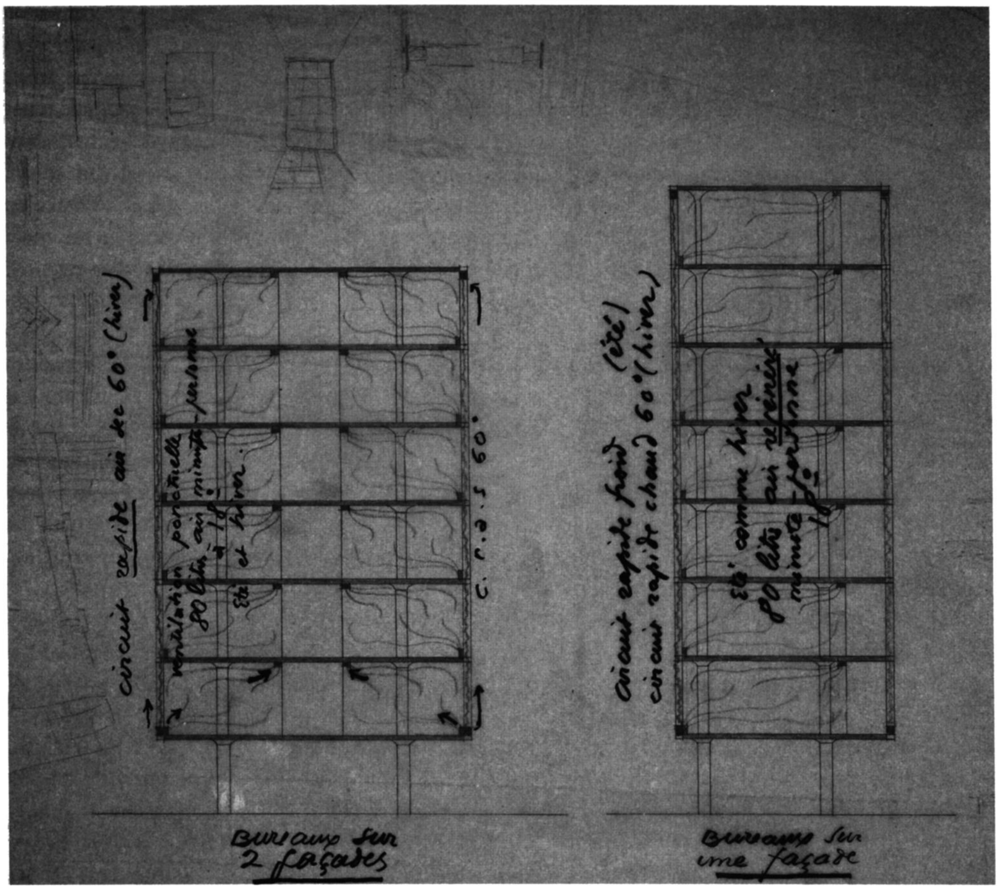

Figure 8. Le Corbusier and Jeanneret, Centrosoyuz, cross sections illustrating the respiration exacte with the mur neutralisants conceived as a full height glass facade. FLC 15912. © FLC/ ADAGP, Paris and DACS, London 2012.

The City of Refuge: a glass debacle

The inadequate development of *respiration exacte* system was also demonstrated by a project that followed shortly after the Centrosoyuz building: the City of Refuge, a hostel in Paris commissioned by the Salvation Army, whose definitive version took form in June 1930. For this building neither traces of the double-skin glass façade, nor diagrams illustrating the principles of the *respiration exacte,* have been found, although documentary sources indicate that the latter were included in the project until 1933.

In the final detail drawings, this building also featured a massive glass curtain wall as the main compositional feature, an element that, as proposed for the Centrosoyuz, would incorporate the innovative heating and ventilation system. The 1,000m^2 of slightly-inclined double-glazed curtain wall covered five floors on the southern façade of the dormitory building. The technology of glass curtain walls was still in its infancy at this time, especially at such a large scale. Whereas the architects had not been able to supervise the construction of the Centrosoyuz building [26], the City of Refuge project, being located in Paris, would have allowed full control of the design and construction of the glass wall. However, the economic austerity that was applied to the project meant that only a single skin of glass could be provided, making the *murs neutralisants* impracticle at a very early stage. Despite this, the almost completely sealed, single-skin glazing system that was installed, used construction details similar to those employed at the Centrosoyuz.

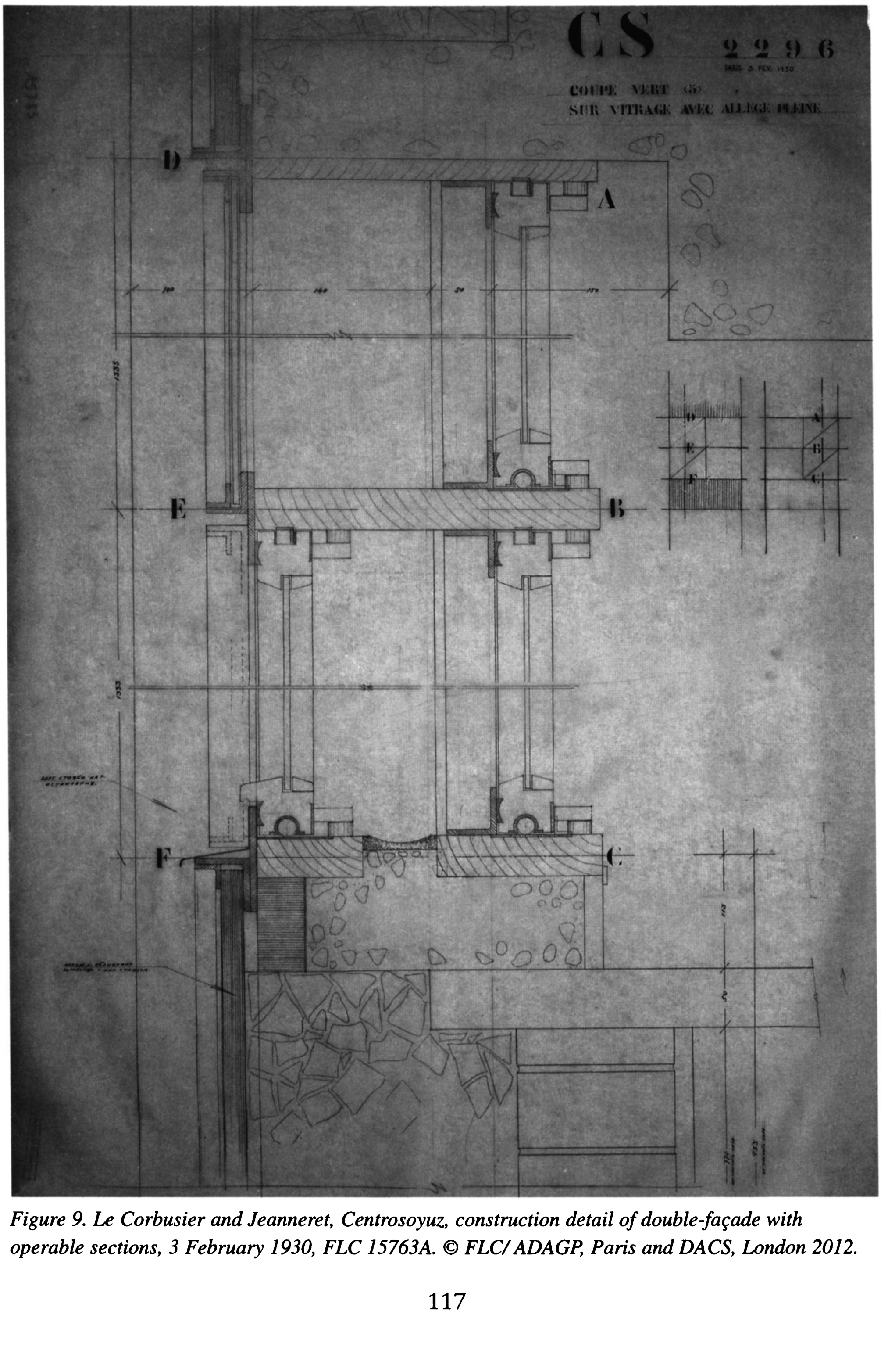

Figure 9. Le Corbusier and Jeanneret, Centrosoyuz, construction detail of double-façade with operable sections, 3 February 1930, FLC 15763A. © FLC/ ADAGP, Paris and DACS, London 2012.

The architects decided to use this building as a *"test case for the authorities"* in order to demonstrate the need for the building codes to be updated

> "The first authorization to build was given on 24 December 1930. It concerned the first three storeys only. The plans submitted to the city included indications for window frames that opened. Mechanical ventilation created a situation that went beyond the scope of the codes which the city architect could not resolve alone. We had to follow the normal channels to obtain a building permit and then defend the mechanical system for ventilation ourselves if the Department of Hygiene raised the issue. The permit for the whole building was given to us on 30 September 1931..." [27].

The architects deliberately chose not to erect the building according to the plans that had been submitted and approved by the municipality in September 1931, replacing the opening windows by a glass facade solution in which only the upper part of three windows on each of the five floors could be opened. Only these general decisions were made by the architects, and the techniques for installing the large surface of plate glass in the façade were left entirely to the initiative of the contractor [28] (Fig. 10).

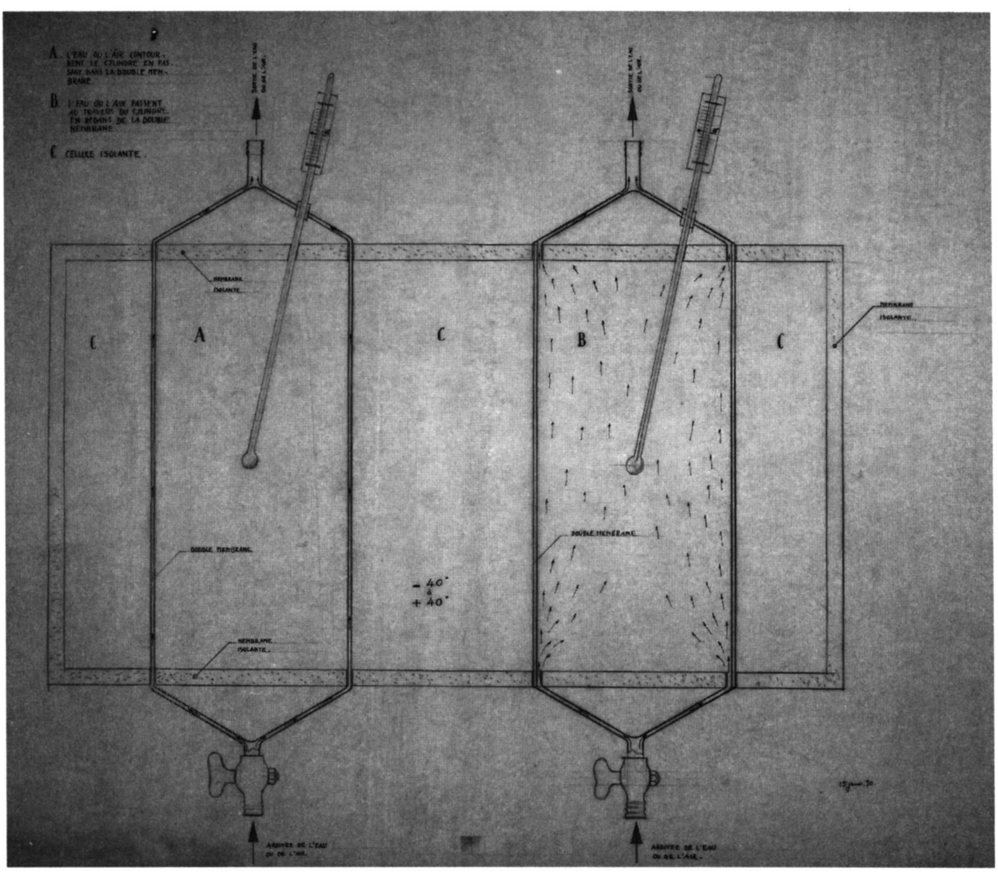

Figure 10. Le Corbusier and Jeanneret, Centrosoyuz, study of the Air Exact plant and the air-conditioning processors, 15 January 1930, FLC 15881. © FLC/ADAGP, Paris and DACS, London 2012.

At the time of specifying the façade system for this building Le Corbusier already had the discouraging report from ABC in his hands. Nevertheless, far from renouncing his invention, Le Corbusier wrote his famous text, La *Respiration Exacte* [29], still filled with enthusiasm. Furthermore, Le Corbusier and Jeanneret sought corroboration of the system's feasibility, in three ways. First, as early as January 1931, the plans of the City of Refuge were sent to at least six firms to obtain technical details and financial estimates. Successive responses arrived in the course of the year, comparing the proposed solution with conventional installations. As expected, they turned out to be extremely expensive, in some cases amounting to half budget for the whole building. Secondly, there was further correspondence between Le Corbusier and ABC asking them to reassess the system. Unfortunately that second report has not been found, leaving us in the dark about their advice [30]. Thirdly, and most importantly, during the first half of 1931, the laboratories of the glass manufacturer Saint-Gobain, under Lyon's direction, commenced a series of experiments to test the system. For this purpose they constructed a full-scale prototype to make measurements, which, in fact, turned out to be the only opportunity the architects had to build their invention [31] (Fig. 11).

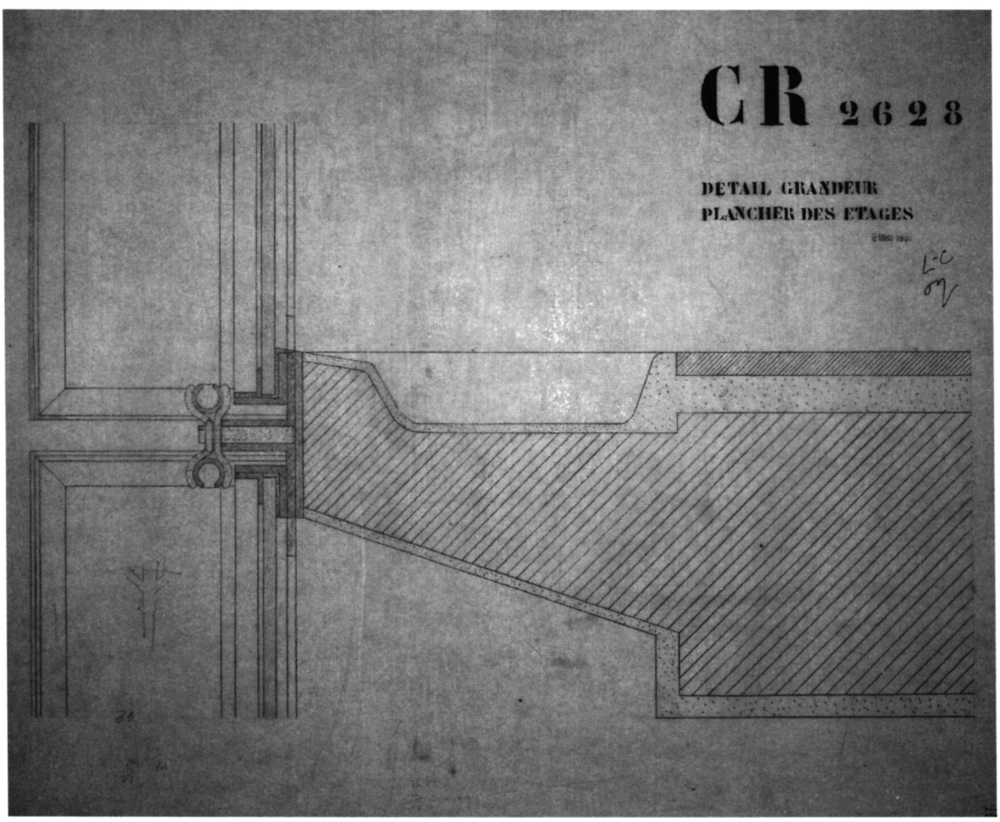

Figure 11. Le Corbusier and Jeanneret, City of Refuge, cross section of the curtain-wall, 9 March 1931, FLC 10732. © FLC/ADAGP, Paris and DACS, London 2012.

Once more, financial constraints affected the environmental strategy for the building. In April 1933 a specific kind of installation and a contractor for heating and ventilation were selected: "a conventional, mixed system of steam heating, mainly with blowers for areas with artificial ventilation, and with radiators for rooms with natural ventilation, was to be installed" [32]. As is well known, the general provision for mechanical ventilation, in conjunction with the overheating produced by the airtight glass-wall, proved to be deficient within just one week of the building's inauguration [33], leading to long disputes that so unjustly tarnished the reputation of Le Corbusier's invention. Despite the strong fight by Le Corbusier against opening windows in the curtain-wall, in January 1935 the Seine Prefecture condemned the infractions of the building code and ordered opening windows to be installed in all parts of the building within 45 days, a result that would, in fact, not take place until 1948.

The Palace of the Soviets: a definitive technical version of the Mur Neutralisant

In September 1931 Le Corbusier's atelier encountered a new project that would take them back to Moscow: they were invited to participate in the competition for the new Palace of the Soviets. This time the environmental engineering design was entrusted to a specialist engineer, Charles Rougnon, whose report included a meticulous description of the proposals [34].

For the Palace of the Soviets, the environmental technology was for the first time regarded with greater rigour but it was not given the same prominence in the images and visualisations for the project as in the two previous buildings. Rougnon recommended the arrangement for the *aération ponctuelle* system in response to two types of uses: one circuit for those rooms that needed constant thermal and air control, such as offices or corridors; and a second circuit for those spaces that would have occasional use, such as the auditoria. To supply the auditoria, one fresh-air lozenge was installed under each seat, resulting in a total of 15,000 inlets. The 1.1m diameter ducts feeding those inlets ran within the floors, and were connected to the main collector at one side, where fans propelled the air. As an additional advantage, this air was pure, since it was not taken directly from the outside, but came from the purifying plant which was made more energy-efficient by locating the return tubes in contact with the cold outside and gain the benefit of passive cooling. The whole building was conceived with its envelope formed by *murs neutralisants*. To reduce noise and thermal exchange with the outside, the auditoria had airtight, translucent and double-glazed *murs neutralisants*, suspended once again from 1.5–2.0m cantilevered slabs. Instead of the banded composition used in the two previous projects, , lights were embedded between the two glass layers to produce a uniform lantern effect at night, an idea Le Corbusier had already proposed for the Assembly Hall of the League of Nations in Geneva, in 1927 (Fig. 12).

Rougnon calculated the heat transfer coefficients (U-values) for the three types of *murs neutralisants* indicated in the competition plans: all-stone façade, all-glass façade, and composite façade consisting of glass bands occupying one third of the wall between floors (Table 1). In both types of the proposed stone façade the resulting coefficient was 0.8W/(m^2.K), with a maximum air cavity of 100 mm to avoid high air circulation speeds that would increase thermal losses. For the glass façade, the best coefficient that could be achieved was rather unsatisfactory, 2.4 W/(m^2.K), and Rougnon recommended complementary experiments by the specialists from *Conservatoire des Arts et Metiers* in Paris to obtain a more feasible solution. The resulting coefficient for the mixed skins was 1.2 W/(m^2.K).

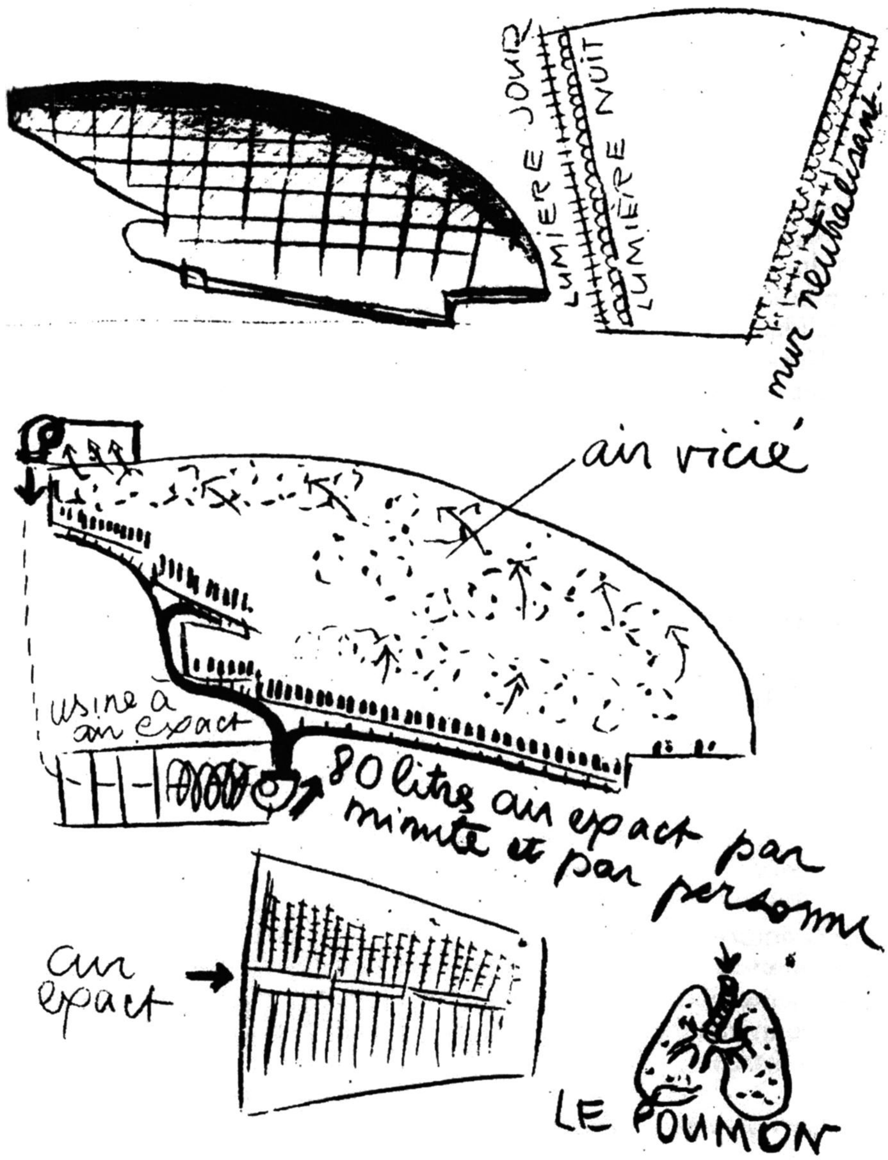

Figure 12. Le Corbusier, air exact system for the Great Assembly Hall in the League of Nations, from Précisions, (Paris: Editions Crès, 1930). © FLC/ ADAGP, Paris and DACS, London 2012.

Table 1. Murs Neutralisants for the Palace of the Soviets

Façade Composition	External Layer		Intermediate Layers	Internal Layer
Stone Facade U = 0.8 W/(m^2.K)	Type A	150mm Artik tuff from Caucasus	100mm reinforced concrete + 80-100mm air cavity	80mm fibrolite (cement + asbestos board with a gypsum finish)
	Type B	120mm Artik tuff from Caucasus	70mm reinforced concrete + 10-20mm insulating board (Celotex or Insulite) + 80-100mm air cavity	40-50mm cement board
Glass Skins U = 2.4 W/(m^2.K)	9mm clear glass		200mm air cavity	2.5mm frosted glass

The eight-page report gave all the heating and ventilation calculations for one of the wings (six-storey building B, each floor 4m high), including the sizes of all types of equipment, and the required air speeds and volume flow. However no images of this installation or the *murs neutralisants* have been found.

Despite the comprehensive elaboration of all aspects of the project, the hopes for a new opportunity for Le Corbusier's team to put their theories into practice were frustrated on 28 February 1932 when the first prize in the competition was finally awarded (ex-aequo) to the design by Ivan Zholtovsky, Boris Iofan and Hector Hamilton.

Later that year, calculations from experimental testing would give final conclusions about the efficiency of glazed *mur neutralisants*. The results from tests run for nearly two years in the new Saint-Gobain factory, based near Paris, were reported in August 1932 in the article *La transmision de la chaleur à travers le verre. Des idées nouvelles sur le chauffage des habitations*, by J. Le Braz, engineer of Saint-Gobain laboratories, and technical writer for the company's bulletin, *Glaces et Verres*.

Le Braz reported that the benefit of the system was that the increase of temperature between the two glass layers enhanced the sensation of comfort near the glass wall, due to the heat exchange between the human body and the interior surfaces of the room. In rooms where there were extensive glass surfaces, the temperature at the glass walls was equivalent to the average of the exterior and interior temperatures, clearly lower than the temperature at the rest of the room's walls. To counter this it was necessary to elevate the temperature of the room. With the intermediate heated void, this increase of room temperature became unnecessary, highlighting the principal advantage of the proposal, among other minor benefits such as its capacity for acoustic attenuation.

As ABC previously stated, the system did not fulfil its main goal: to behave as a neutralising envelope that moderates the internal impact of external temperatures. In this regard, Le Braz suggested that the neutralising properties of the system could be improved, by delivering the appropriate level of internal environmental comfort, while avoiding excessive energy consumption for heating, through the use of a triple glass wall. This triple façade would have the air circuit flowing between the interior and the intermediate glass panes to provide the warming effect for the interior, and a motionless air layer between the intermediate and the exterior glass panes to provide the desired thermal insulation; but of course, this would still not have eliminated the need for a conventional space-heating system.

Despite this setback, Le Corbusier continued his research on the *mur neutralisant* in the following years. Not only was the report of Saint-Gobain's experiments published and reviewed on several occasions, as part of his Radiant City ideology, but also the system was included in his housing and office competition projects of the 1930s. From the Immeuble Clarté project (Geneva, 1930-2) onwards, the same scheme but "in a mode of architecture that was infinitely superior" [35] was proposed for all his *immeubles* prior to World War II, clearly illustrating the principles of his *Radiant City*. All of them featured the use of a steel structure, dry construction systems for the façades, and large expanses of glass showing the same pattern of horizontally-banded elevations, with the consequential benefits of integrating sunlight, open space and vegetation. Whenever there was scope in the budget, Le Corbusier and Jeanneret prescribed glazed *murs neutralisants*, for example in the designs for the long facades of the *Immeuble Locatif* and the *Immeuble Rentenenstalt* (Zurich, 1932 and 1933 respectively) [36]. The system was not further developed though, probably due to the fact that neither of the projects was executed. In *Immeuble Locatif* Le Corbusier only mentioned the use of the *respiration exacte* in his *Oeuvre complète* [37]. In *Immeuble Rentenenstalt,* the system was described in the chapter about air-conditioning contained in the *Rapport Annexe* that formed part of the competition entry, complemented by some conceptual diagrams and axonometric views found among the project drawings, where the "exact-air" plant seems to be the focus (Fig. 13).

Conclusions

The working principles behind the *mur neutralisant* had emerged before Le Corbusier, notably in the Russian context, where the Winter Palace had set a clear precedent in actively warmed double-skin windows. In the *mur neutralisant*, the innovation was in translating previous ideas to a greater scale, principally with regard to the use of glass. To that end, the increase in scale from single window to the entire curtain-wall implied a fundamental re-think of this component within the building: the incipient embodiment of a new function converted the facade into a machine that would project its potential on the rest of the building.

Le Corbusier understood that by endowing the building envelope with the means of becoming performing unit, the building would acquire its own autonomy, constituting a self-sufficient system whose independence would imbue it with a universal character as well. This idea of a neutralising surface fitted perfectly within the universe of building elements with which he was starting to forge his vocabulary for a "machine-age architecture", one that embraced prefabricated, standardized, and universal components that would form his basic concept of "la maison *équipé*". Thus, the value of the *mur neutralisant* lay in foreseeing the importance of "mechanising" the transparent façade of the future: his first "mechanical window" [38] would lead to the "machine-façade".

However, Le Corbusier's approach to comfort showed certain contradictions: his search for thermal and acoustic insulation, and careful avoidance of condensation damage (using channels allocated in the perimeter of the slabs), and draughts (by sealing the façade) conflicted with the poor provision of natural ventilation and heating (eliminating opening windows and radiators), and the unshielded glass surfaces (disregarding the greenhouse effect and the corresponding overheated interior in favour of "healthy" sunlight). Le Corbusier's belief, that optimising the hygienic condition of the living environment was more important than thermal comfort, was ratified in his own words: *"Like in the City of Refuge, the glass-wall of the Swiss Pavilion is south-facing; but this glass-wall has windows. The students' rooms are provided with conventional radiators. After one year of use, this month we have witnessed the cleaning operations: it was necessary to wash all the walls in the communal spaces and bedrooms, blackened with dust and soot. This dirt enters through the windows; in winter it is concentrated by the convection currents from the radiators...Only the City of Refuge is protected from this deficiency!"* [39].

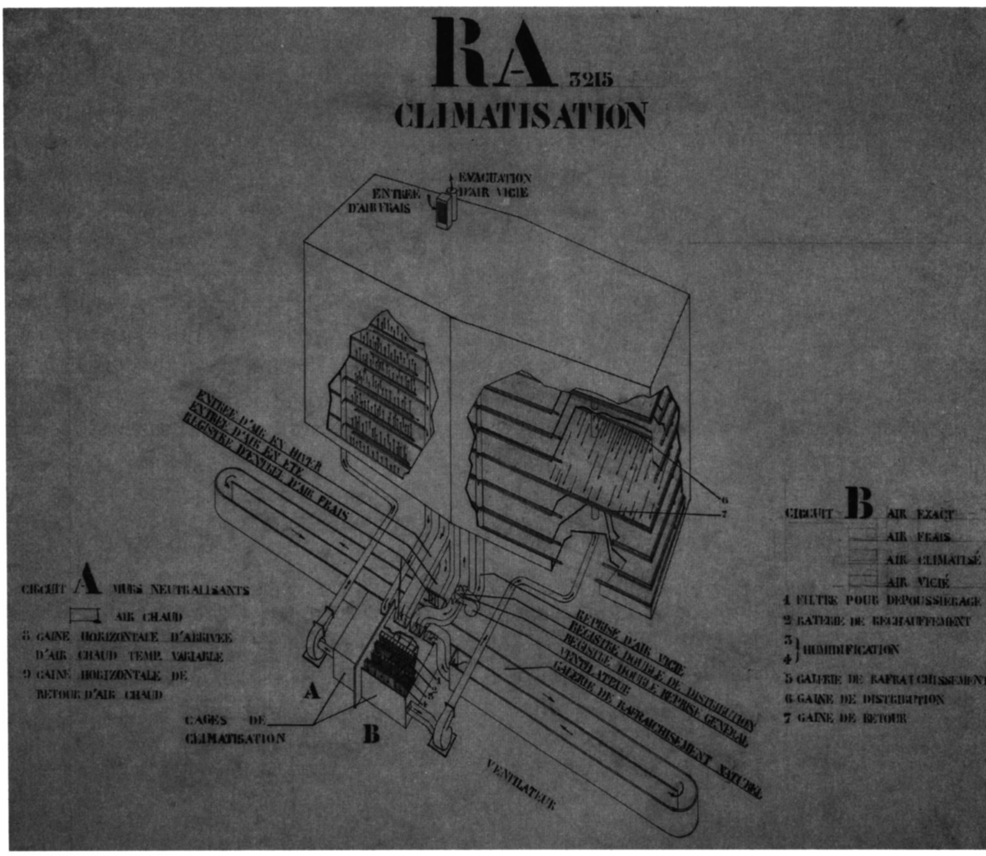

Figure 13. Le Corbusier and Jeanneret, Immeuble Rentenenstalt, study of the aération ponctuelle and murs neutralisants, 16 December 1933, FLC 23467. © FLC/ ADAGP, Paris and DACS, London 2012.

By the end of the 1930s, the development of the original concepts of the *respiration exacte* and the *mur neutralisant* systems had come to an end. World War II was a turning point in Le Corbusier's work, and his environmental ideas would also take a new direction. The next stages in the development of the *mur neutralisant* have frequently been wrongly associated with one of Le Corbusier's favourite elements from his late period, his architectural sunscreens called *brise-soleils*. When Le Corbusier offered to rebuild the airtight glass-wall of the *City of Refuge* in 1948, finally incorporating windows, he also proposed installing *brise-soleils* over its entire façade. This has led to the widely held, but mistaken view expanded by Reyner Banham and other scholars [40], that the *brise-soleil* emerged to replace the discredited *mur neutralisant*. It also led to the view that the widespread use of the *brise-soleil*, in his later work marked a rejection of the technologies in which he had believed at the start of his career, demonstrating his faith in the efficiency of the new passive system. On the contrary, Le Corbusier's interest in a technological glass façade persisted during his entire career, evolving through different degrees of expression, and progressing towards a more subtle presence. In an intermediate stage Le Corbusier, in fact, investigated how to complement (and not replace) the *mur neutralisant* using passive solar-control, by adding *brise-soleils*. This arrangement was vehemently defended for the façade of the United Nations Building in New York during the period when Le Corbusier led this project's design team (1947-48). In a third and final stage, the neutralised glass-wall developed towards a more synthetic version: Le Corbusier decided to use a successful commercial product, *Thermopane* Insulating Glass Units [41], which would allow him to realise his concept of a standardised-component, insulated glass wall. At this time (1951-63) he anticipated a holistic glass wall, offering a separation of its various functions, seeing the glass surface as a zoned plane with specialised areas for ventilation, views, sun-control and decoration. Fully developed examples of this concept were built in the *Maison du Brésil* (Paris, 1957-59), and the Carpenter Center for Visual Arts at Harvard (1959-63).

Le Braz's proposal of a triple glass skin could be seen as favourable to Saint-Gobain's interests, due to the addition of an extra glass layer to the original design. But, in fact, this solution he was an early precedent for the contemporary "exhaust-air façade" [42]. A successful development of Le Braz's version of the *mur neutralisant* was used 50 years later in the Lloyd's Building in London (1978-86) designed by Richard Rogers, and multi-layered glass-walls using triple insulating glass units are now widespread in energy-efficient buildings ranging from the Office Building in Würzburg designed by Webbler and Geissler (1995), to Herzog and Partner's Trade Fair Headquarters in Hannover (1999), David Chipperfield's library in Des Moines (2005), or Steven Holl's Nelson-Atkins Museum of Art in Kansas (2007). indeed, they have become part of the *lingua franca* of contemporary façade technology.

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References

[1] See H. Sobin, "From l'Air Exact to l'Aérateur. Ventilation and its evolution in the architectural work of Le Corbusier" in K. Tanzer and R. Longoria, (Ed.) *The Green Braid: Towards an Architecture of Ecology, Economy, an Equity*, London: Routledge. 2007. pp.142-3: "*...l'air exact* and the *mur neutralisant* henceforth gradually disappeared from his later writings and projects." And: "...the architect appears to have begun to lose faith in his earlier machine-oriented philosophy."

[2] R. Banham suggested that the *brise-soleil* was invented shortly after the fracas over the glazing of the City of Refuge due to overheating problems: "a Le Corbusier motivated by desperation would invent, shortly after, an external solar protection or *brise-soleil*", in *The Architecture of the Well-Tempered Environment*. Chicago: The University of Chicago Press, 1984 (c1969), p. 158. Sobin proposed: "this experience would undoubtedly impel the architect to speed up the development of the *brise-soleil* mechanism (underway since 1933), in "From", *Green*, (Note 1), p. 142. B. Maurer traced the *brise-soleil* as a consequence of the bad luck experienced in the competition for the Rentenantalst building, for which the use of the *mur neutralisant* and *respiration exacte* were envisaged, in "Immeuble Rentenantalst", *Le Corbusier Plans*, DVD 6.

[3] J. P. Traisnel, 'Le métal et le verre dans l'architecture en France. Du mur à la facade légère' (Ph.D. thesis, Université Paris VIII-Saint-Denis, 1997), p.210-19.

[4] Double-glazed windows were common in Europe at the end of the 17th century (i.e. Somerset House in England, 1661; and Manor House in Zeist, Holland, 1686). See H. J. Louw, "The Origin of the Sash-Window", *Architectural History*, 26 (1983), pp.49-150. First references to the storm window are accounted in a French construction manual from 1691, C.A.D'Aviler, *Cours d'Architecture*, see S. Lietz, *Das Fenster des Barock. Fenster und Fensterzubehör in der fürstlichen Profanarchitektur zwischen 1680 und 1780*. Munich: Kunstwissenschaftliche Studien 54, 1982, p.123.

[5] Articles by P. Patte (1777), T. Tredgold (1824), M. Wyman (1846), or J. Drysdale and J. Hayward (1872) proposed different models. See J.P. Traisnel, *Métal,* (Note 2) pp. 294-7. The Steiff factory erected in Giengen, Germany (1903) seems to be the first double-skin glass facade ever built.

[6] J.L. Barona, "Génesis y dimensiones del higienismo", *Lars Cultura y Ciudad. Higienismo y Arquitectura*, 15 (2009), pp.15-19.

[7] Le Corbusier was a fervent pro-hygienism man, broadly manifested in his writings. His proposition of the hermetic envelope is firmly based on scientific studies of air pollution: see for instance his remark about Dr. Martini's work in Le Corbusier, "La Respiration Exacte", *La Ville Radieuse*. Boulogne-sur-Seine: Éditions de l'Architecture d'Aujourd'hui, Collection de l'équipement de la civilisation machiniste, 1935, pp.41, or the use of Dr. d'Arsonval and Dr. Poirier experiments on ventilation, described in G. Lyon, *L'Acoustique Architecturale, avec l'annexe: L'Aération Moderne des Salles* París: Film et Technique, 1932, p.56-58.

[8] See air-conditioning devices in Le Corbusier, *La ville*, (Note 6) p.46 or Raoul Decourt's Maison Isotherme product advertised in L'Esprit Nouveau.

[9] Le Corbusier worked intermittently with his cousin Pierre Jeanneret. The *murs neutralisants* of the 1930s were developed together with Jeanneret, although it was Le Corbusier who presented and defended the device in his writings and lectures.

[10] Handwritten note, Le Corbusier to Pierre Jeanneret, Moscow, Oct. 1928, FLC. "*Pierre, revoir tout le système fenêtres. On pourrait éventuellement tout vitrer et chauffer entre deux. Consulter G. Lyon et laboratoire. Etudier 1 chauffage à eau chaude p. bureaux [et] 1 chauffage à air chaud par double cloison vitrée pour empêcher le froid.*" An similar postcard was sent to Gustave Lyon. Paris: Centre d' Archives d' Architecture du XXe Siècle, Dossier 237 Ifa 1/3.

[11] Patent (*Brevet d'invention*) n. 681.311, gr. XV, cl. 4, registered 28 Jan 1934, "Procédé et dispositif pour la ventilation de locaux"; and patent (*Brevet d'invention*) n. 766.756, gr. XV, cl. 4, registered

23 April 1934, "Dispositif pour la ventilation d'un local". Paris: Centre d' Archives d' Architecture du XXe Siècle, Dossier 237 Ifa 6/2.

[12] See G. Lyon, *L'Acoustique*, (Note 6) pp.56-60; and Le Corbusier, "Pour chauffer et pour ventiler la salle"; and Le Corbusier, "Pour éclairer la salle", *Une Maison – Un Palais. A la recherche d'une unité architecturale*. París: Crès, 1928.

[13] T. Benton, "Pessac and Lège revisited: standards, dimensions and failures". *Massilia, Annuaire d'études corbuséennes,* 3 (2004), p.91-96.

[14] Examples of heated double skins can be found in German, Russian and British glasshouse construction of the 19th century, as discussed in J.C. Loudon's *Remarks on the Construction of Hothouses* (1817) and C. McIntosh's *The Book of the Garden* (1853). This arrangement was present in two later celebrated precedents: the Glasgow School of Art (1897-1909) by Charles Rennie McKintosh, and in Paris the Lyceé Victor Hugo (1896-96) by Anatole Baudot. See Traisnel, *Métal,* (Note 2) pp.294-7.; and R. Bruegmann, "Central Heating and Forced Ventilation: Origins and Effects on Architectural Design", *The Journal of the Society of Architectural Historians*, 37, 3 (Oct. 1978), pp.143-160.

[15] A circuit of hot air between the double-pane glass windows was planned for the Winter Palace in St. Petersburg as early as 1883. See N. Sergueeff, "Chauffage et ventilation du Palais de l'empereur de Russie", *Nouvelles Annales de la Construction*, (Janvier 1883), pl.3-4 ; and M. A. Wedeniapine, "Système de chauffage du Palais d'Hiver à Saint-Pétersbourg", *Nouvelles Annales de la Construction*, (Juillet 1884), col. 102-04.

[16] J. Caron, "Une ville de Le Corbusier, 1916", *L'esprit nouveau*, 6 (March 1921), p.687:
"*Une pièce peut être surchauffée, la grande verrière enverra malgré tout des ondes continues d'air refroidi au coeur de la salle, la rendant inhabitable (...). Le Corbusier-ingénieur à fourni lui-même la solution à Sulzer (installateur de chauffage central): il fit passer des tuyaux de chauffe entre les deux parois de la double verrière; d'une surface refroidie, il fit une surface neutre*".

[17] Descriptions of both systems in Le Corbusier's writings: *Précisions sur un état présent de l'architecture et de l'urbanisme*. Paris: Crès , 1929, p.85; and *La* Ville, (Note 5) p.40.

[18] See letter from Nikolai Kolli, one of the members of the Russian board who went to Paris to collaborate in the development of the plans, to Le Corbusier and Jeanneret, Moscow, 7 March 1929, FLC:
"*...Le projet que nous avons apporté à Paris est considéré ici avec un intérêt tout à fait exceptionnel. La direction du CS trouve qu'il correspond à tout leurs désirs. Au point de vue de la composition architecturale, on n'y trouve pas de défauts. Mais on craint d'avoir de grandes difficultés économiques en faisant le chauffage que vous avez proposé.*"

[19] Letter from Le Corbusier to Mr. F.R. Still (ABC 's Vice-president), 3 January 1930, FLC:
"*Je serais désespéré si notre bâtiment (dont tout le monde parle) était muni des anciens systèmes de chauffage. Ce serait une défaite....Votre réponse urgente serait indispensable. Je n'attends de vous qu'un calcul encore approximatif mais suffisant pour répondre oiu ou non.*"
Lyon made a scale model of a double-glazed unit to produce the first measurement of its performance, with a promising outcome, but the actual results of those preliminary studies were not enclosed. See comment by J. Le Braz, "La transmission de la chaleur à travers le verre. Des idées nouvelles sur le chauffage des habitations". *Glaces et Verres,* 29 (Aug-Sept 1932), pp. 12. And see note by M. Krug-Basse (collaborateur de Gustave Lyon) "sur le chauffage d'un local par circulation d'air entre deux parois de verre" (1929). Paris: Centre d'Archives d'Architecture du XXe Siècle, Dossier 237 Ifa 10/32, 1929-30.

[20] Plan CS20 2088, FLC 15690.

[21] The idea of the grid must have followed the previous layout proposed by Lyon for the Assembly Hall of the League of Nations, in which there was an "exact air" inlet underneath each seat supplying purified and ozone-enriched air to the mouth of each person. This arrangement was based

on the theories developed by Dr. d'Arsonval on ventilation, as can be read in G. Lyon, *L'Acoustique*, (Note 6), p. 56, 59.

[22] Plans CS 2265/FLC 15726 and CS 2266/FLC 15727.

[23] Plan FLC 15912, no date.

[24] Letter from Mr. Still to Le Corbusier, 24 January 1930, FLC.

[25] The engineer P.N. Sabarov designed the metal frames. See J.L. Cohen, *Le Corbusier et la mystique de l'U.R.S.S. Théories et projets pour Moscou. 1928-1936.* Brussels : Pierre Mardaga, 1987, p.102.

[26] Ibid., p.120. Le Corbusier visited Moscow for the last time in March 1930 to witness the first operations in the site. After that, it was mostly Kolli who struggled to supervise the building's construction in conformity with the original plans.

[27] Annotated note by Pierre Jeanneret on contacts with the architectural services of the city concerning the mechanical ventilation system (FLC, item 127, no date) in B. B. Taylor, *Le Corbusier. The City of Refuge, Paris 1929-33.* Chicago: The University of Chicago Press, 1987 (c1978), pp. 113 and 183.

[28] E. Gallo and V. Fernandez, "Factory", *Docomomo (*Note 7):
"Based on summary sketches made by the office in 1931 several firms tended for the construction. Two of them were retained, MMM (a special steel drawn profile for the large frame) and D&L (U,L,T and Z steel profiles for the façade on Chevaleret street)".

[29] Le Corbusier, "La Respiration Exacte", winter 1931-1932, FLC.

[30] Letter from Le Corbusier to Mr. Still, 7 July 1931, FLC.

[31] See Urbano, R. "Le Pan de Verre Scientifique: Le Corbusier and the Saint-Gobain Glass Laboratory Experiments (1931-32)" (Architectural Research Quarterly, in press).

[32] For a detailed relation of the heating and ventilation systems installed see: Taylor, *Corbusier*, (Note 26) pp. 95-97 & 111-115; and Gallo, "Factory", *Docomomo (*Note 7).

[33] See B. B. Taylor, *Corbusier*, (Note 26) pp. 111-122.

[34] C. Rougnon, "Construction du Palais des Soviets à Moscou. Etude de l'acoustique des grandes salles couvertes. Etude de l'acoustique en plein air. Avant-projet de chauffage et ventilation", 14 January 1932. Paris: Centre d'Archives d'Architecture du XXe Siècle, Dossier 237 Ifa 11/32. Same report, dated 24 December 1931, FLC.

[35] Le Corbusier to Rudolf Fueter, 8 May 1933, FLC.

[36] It is likely that the system was intended for the *Immeuble aux Invalides* (Paris 1932), the *Immeuble GB Boulogne-sur-Seine* (France 1933), the *Immeuble Dubois et Lepeu* (Paris 1934), the *Immeuble pour ouvriers* (Zurich 1934) and the *Immeuble à Montmartre* (Paris 1935), since all of them followed the same model. Nevertheless, there is no concrete evidence of this, although it should be remembered that many of the plans were never recovered after being submitted to the competitions.

[37] Le Corbusier and Jeanneret, *Oeuvre Complète, 1929-34*. Zurich: Verlag DR. H. Girsberger, 1935, p.95.

[38] Le Corbusier advertised the potential of their standardised sliding windows as mechanisms: "The window is the mechanical element-type of the home" ("*La fenêtre est l'élément mécanique-type de la maison*"). In "Appel aux industriels", *Almanach d'architecture moderne*. Paris: Crès, 1926, pp.102-3.

[39] Letter from Le Corbusier to Colonel Isely, 9th November 1934, FLC.

[40] See Note 2.

[41] Thermopane was brought to the market in 1935 in the U.S. It comprised two sheets of glass hermetically sealed with a 12mm air gap, applied directly onto the reinforced concrete *in situ* within the structure, thereby constituting a sealed sheet of glass without joinery.

[42] C. Schittich, et al, *Glass Construction Manual*. Basel: Birkhauser, 1999, p.146.