The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Ventilation Concept, Indoor Air Quality & Measurement Results in the "Passivhaus Kranichstein"

W Feist*, J Werner**

* Institut Wohnen und Umwelt, Annastr 15, D-64289 Darmstadt, Germany

** Ingenieurbüro ebök, Reutlinger Str. 16, D-72072 Tübingen Germany

1 Synopsis

The "Passivhaus Darmstadt-Kranichstein" is a 4 unit terrace house with an extremely low total annual energy consumption of less than 32 kWh/m^2 of living area, thereof about 12 kWh are needed for room heating /Feist 1994/. The determinig factors for the low consumption are the superinsulation, airtightness of the thermal envelope in combination with a highly efficient VAV ventilation system, and an improved window construction.

The "Passivhaus" therfore is a typical example of an improved low energy house. The results of a detailed monitoring program allow decisive statements concerning reduction of energy consumption, relief of environement, indoor air quality, and thermal comfort.

The key results concerning indoor air quality can be stated as follows: The concept of a low energy building with mechanical ventilation system combinated with low emission materials inside the house guarantees good indoor air quality and thermal comfort at relatively small air exchange rates and very low heating demand.

2 Research Project Passivhaus

The "Passivhaus" was planned by the architects Prof. Bott/Ridder/Westemeyer, scientific consulting was done by the "Institut Wohnen und Umwelt" (IWU) and Prof. Bo Adamson (Lund University). The house was built in 1990/91, since October 1991, 4 families have been living in it. A grant was given by the "Hessisisches Ministerium für Umwelt, Energie und Bundesangelegenheiten" (HMUEB).

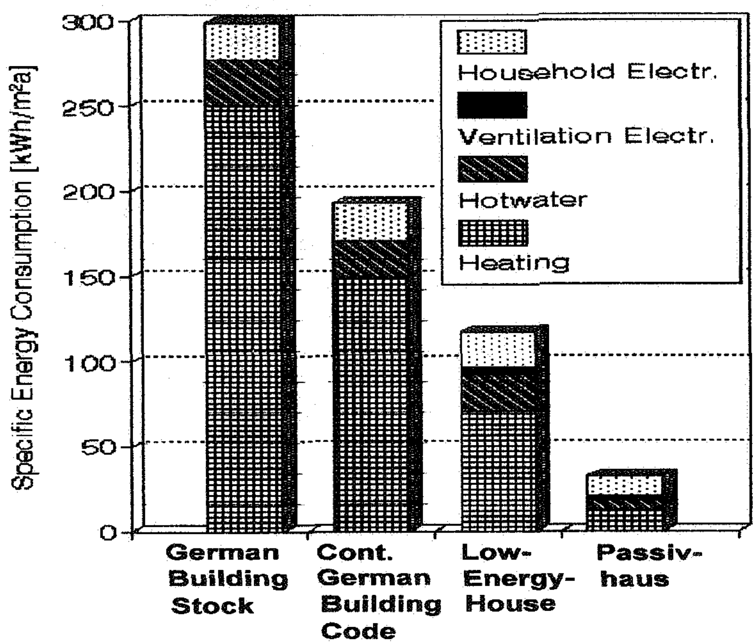

Fig. 1: Spec. energy use: average of German stock, contemporary German building code, low energy house, Passivhaus

The first objective of the reserach project was to check the possible amount of energy savings for heating, hot water and household electricity by passive measures. An analysis of the energy balance over two years demonstrated that the expected reduction of 90% was attained compared to the average contemporary German consumption (Fig. 1).

The monitoring program (Oct 1991 to Sept 1993) was performed by the consulting office "ebök" under contract of the "Wüstenrot Stiftung Deutscher Eigenheim e.V". With grants of HMUEB the program is continued.

3 Passivhaus Darmstadt-Kranichstein

The building is east-west-oriented with an unshaded south facade and has a relatively small surface/volume ratio. The heated floor area of each unit amounts to 156 m^2. The thermal envelope is superinsulated, high effort was put into reduction of thermal bridges and air leakages. Tab. 1 shows the construction of the thermal envelope /Feist 1993/.

Tab. 1: Thermal transmittance of the building envelope

element	construction (warmside to coldside)	U-value [W/m^2K]
roof	water based color, wall paper, gypsum board, spacer battens, PE foil with plastered jointings to the walls and carefully glued and fixed overlaps, I-stud framing system (masonite beam) 445 mm insulated with blown in rockwool, formaldehydefree particle board plastic foil, turf roof.	0.10
wall	water based color, wall paper, gypsum plaster as airtight layer, calcium silicate blocks 175 mm, 275 mm expanded polystyrene foam (EPS), reinforced lime cement plastering.	0.14
ground floor	parquetry with solvent free coating, cement plaster, 40 mm EPS sound insulation, concrete slab, 250 mm PS insulation with reinforced coating.	0.13
window	krypton filled triple glazing with double low-e-coating, additional insulation by CO_2-expanded PU foam moulding of the wooden frames and the outer 25 mm of the glass perimeter.	0.70

The airtightness of the houses is very good, pressurization tests conforming /SS 021551/ yielded air change rates of 0.2 to 0.4 ac/h at 50 Pa pressure difference.

Tab. 2: Measured specific energy consumption

spec. energy use per m^2 heated floor area		period 91/92 [kWh/m^2a]	period 92/93 [kWh/m^2a]
household	electricity	6,27	6,17
ventilation	electricity	2,65	2,93
others	electricity	2,85	2,10
cooking	natural gas	2,43	2,60
hot water	natural gas	8,28	6,12
heating	natural gas	20,81	11,91
total		43,29	31,83

The energy balance is listed in Tab. 2. Period 91/92 covers Oct. 91 to Sep. 92, period 92/93 Oct. 92 to Sep. 93. The differences between the two periods are mainly caused by the fact that the insulation of the ground floor and the window frames were finished in May 1992.

Compared to the average of the German dwelling stock, the heating energy use was reduced to 1/20, the total energy use was reduced to 1/10.

4 Ventilation

4.1 Ventilation Strategy

The ventilation in a house has to guarantee acceptable indoor air quality and thermal comfort.

Uncontrollable in- and exfiltration caused by weatherdependent forces through leakages in the thermal envelope is not suitable for a demand controlled ventilation. Neither placement of the leaks nor the amount or direction of the air flow is controllable. Additionally, there is considerable risk for moisture damage and draughts.

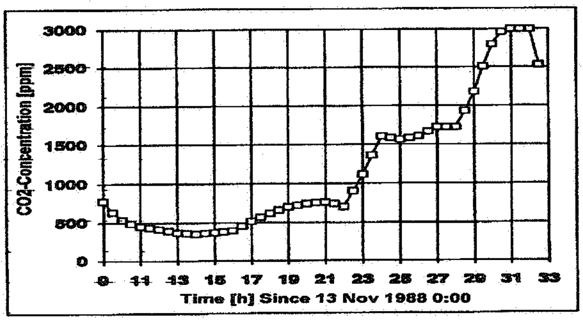

Fig. 2: CO_2 concentration in the bedroom of a modern German building without mechanical ventilation system, windows and doors closed. (Upper limit of range of measuring device 3000 ppm).

Natural ventilation of rooms by opening windows is the traditional and most popular way in Germany. There are no additional investment costs. But often it is difficult to open and close the windows regularly. A typical example for this is the situation in a bedroom with closed windows and doors. During night CO_2 concentration exceeds 3000 ppm (Fig 2), this is a indicator for bad indoor air quality. Continually opened windows result at wintertime in to high air volume flows together with dry air and increased ventilation losses.

A well established solution for a demand controlled ventilation sytem in low energy houses is a exhaust system (ES) /Blom 1990/, used in Sweden since more than 50 years. Air is extracted by fan from kitchens, bathrooms etc. Fresh air enters the house from outside by specially designed vents in living- and bedrooms, but also by other leakages in the building envelope. In an airtight house, a well planned and installed exhaust system this is a good tool to maintain acceptable indoor air quality. There is no heat recovery from exhaust air, but by demand control, it is possible to reduce air flow rates keeping a good air quality. This also results in reduced ventilation losses.

Supply-exhaust-systems (SES) with heat recovery by an air to air heat exchanger can reduce ventilation losses furthermore. There are increased investment costs and a higher electricity consumption compared to exhaust systems. Practical experience in low energy houses shows that installation of SES is only useful, if the following requirements are fulfilled:

- Efficient air exchangers (>75% heat recovery effectiveness) and low electricity consumption, so that the ratio between savings of heating energy and electricity consumption is better than 4.
- Buildings have to be very airtight. Otherwise significant heat losses are caused by additional infiltration, wich are not reduced by heat recovery.

- Proper maintenance of system and filters is undispensible, only clean systems guarantee good indoor air quality.

Nowadays an economical operation of SES in residential buildings in Germany is an exceptional case. Therefore, we usually recommend exhaust systems for normal German low energy houses, wich are simpler and more cost effective.

4.2 Mechanical Ventilation System

For an advanced low energy house like the Passivhaus a highly efficent heat recovery system is undispensible.

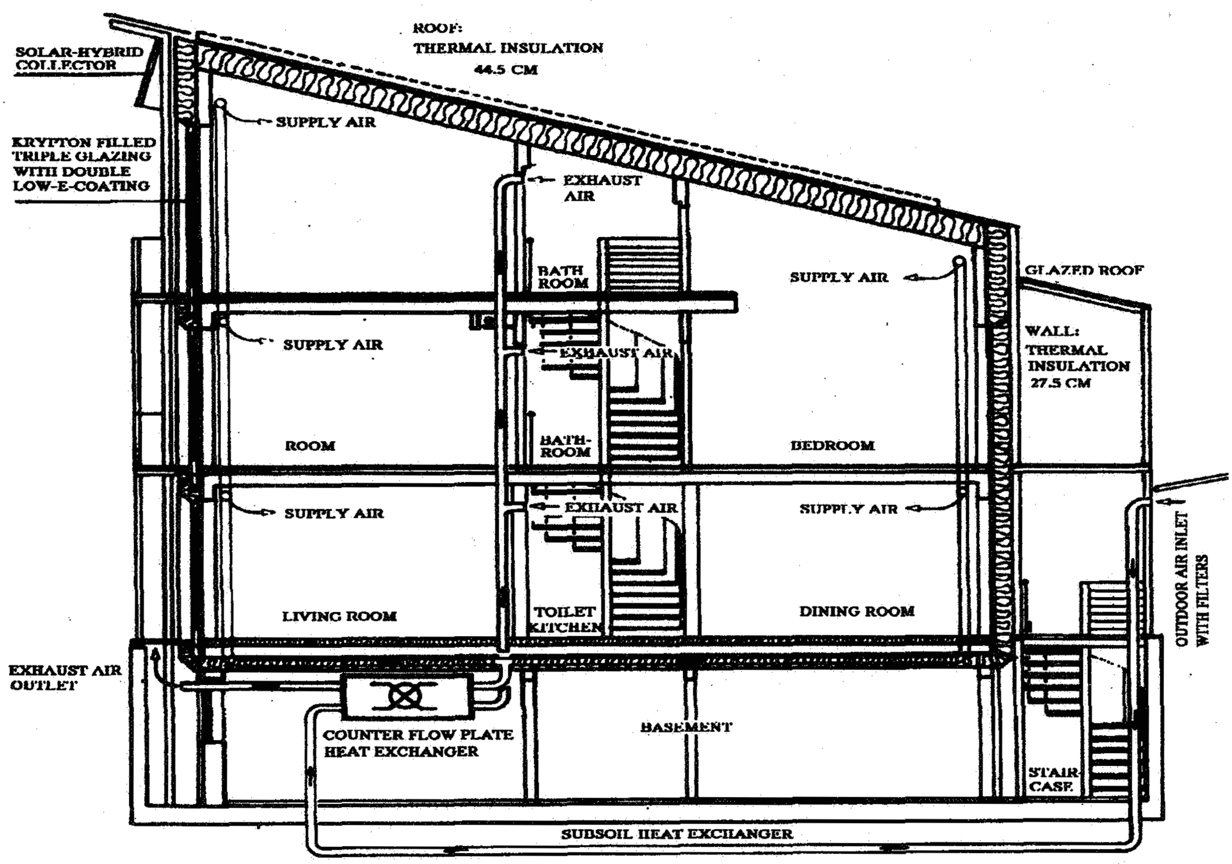

Fig. 3: Integration of the ventilation System in the Passivhaus

Each unit is equipped with a VAV ventilation system. Fig. 3 shows a vertikal sectional view with the arrangement of the ventilation system. Fresh air enters the system by a filter combination (EU3/EU8) at the north front and gets via the subsoil heat exchanger 1 m below the basement floor to a counterflow heat exchanger situated in the basement. At the entrance of the fresh air there is an additional test filter. Supply air ist distributed to the living area, exhaust air is taken from toilets, bathroom, and kitchen and drawn to the heat exchanger. The DC-driven fans are placed in the cabinet of the heat exchanger.

The supply air distribution can be varied (30%/70%) between the living area in the ground floor and the rooms in the upper floors, the exhaust air distribution as well between the rooms in the ground floor and the upper floors. This is done by motor controlled dampers. The air flow rate can be switched to 4 levels (0, 60, 100, 180 m^3/h). Both can be done manually or by a computerized control system. In the automatic mode the air flow rate and the supply air distribution is controlled by CO_2 concentrations in the ground or upper floors, the distribution of exhaust air is controlled by relative humidities.

Both in manual and in automatic mode the inhabitants can change the exhaust air distribution by local demand switches, realeased automatically after a period of time. During cooking, the air flow rate of the cooker hood is boosted by an additional AC-driven fan.

The air flow rates are designed to reduce and control the unavoidable emissions (odour, humidity and CO_2), related to human activity in residential buildings. Other emissions from building materials, furnitures, household products etc. should be minimized by proper selection of materials.

Taking Pettenkofer's number of 1000 ppm CO_2 /Pett 1858/as an upper limit for human caused loads, a minimal air flow rate of 25 m^3/h per person is necessary. An air flow rate of 100 m^3/h is sufficient for 4 persons. The total air exchange rate in the Passivhaus (0.22 ac/h) seems to be rather low. However, using the dampers to adjust air distribution on demand, this results in higher air exchange rates (0.5 ac/h and higher) in single rooms during presence of persons. The controlled interzonal airflow from the living area to bathroom, toilet and kitchen is also sufficient to remove humidity and odours.

Ventilation system and air flow rates were correctly installed and adjusted. Air ducts consist mainly of metal sheet coated with zink. The glasswool in the flexible sound attenuators is covered by perforated metal sheet. Duct joints are fixed by screws and taped thorougly, airtightness of ducts inside the thermal envelope was checked by pressurization.

The subsoil heat exchanger consists of flexible, corrugated synthetic pipes without joints under the ground plate. An inspection by video camera in october 1992, after one year of operation, showed all pipes clean and undamaged. At that time, no condensated water was present, although during some periods in spring and summer the presence of condensated water is suspected.

4.3 Measured Energy Results

Fig. 4 shows the measured air flow rates in one ventilation system of the Passivhaus during a typical day, 23 October 1993. It was a cloudy weekend day and all 4 inhabitants were at home. During nighttime the air flow amounts constant to about 100 m^3/h, during daytime air flows changes according to the activity of the inhabitants.

Fig. 5 shows the measured heat recovery effectiveness of the ventilation system. The mean effectiveness of the complete system at this day amounted to 94 %.

The annual electricity consumption of the complete ventilation system (fans, measuring and control system, motor drives), measured by a separate electricity meter, amounted to 457 kWh. Such a low consumption could only be achieved by changing the fans from AC to DC driven motors.

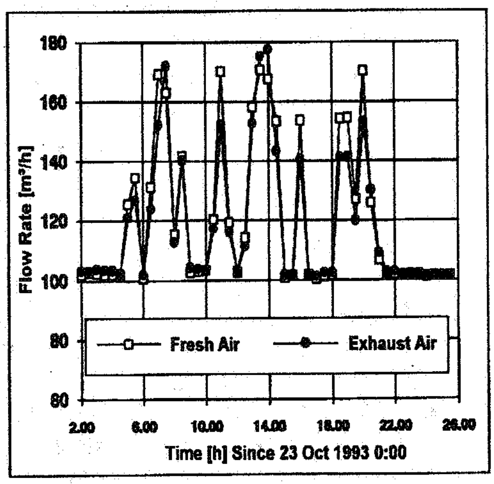

Fig. 4: Measured air flow rates in one ventilation system of the Passivhaus

5. Indoor Air Quality: Results and assessment

The primary purpose of ventilation is good indoor air quality. The Passivhaus is a very good test object to check the correlation between the operation of the system and the indoor air quality: detailed planning, thorough construction and verification by measurements of the physical properties of the existing building and ventilation system amounted in the result of a system complete in working order.

In 1993 the monitoring program therefore was extended to check the indoor air quality too. In addition to the continuos measurement of the energy balance, comprising also CO_2 and relative humidity, the levels of different VOC, dust, spores and radon were tested at different times. The air quality measurements were performed by "eco Umweltlabor Köln" under contract of IWU and supported ba a grant of HMUEB.

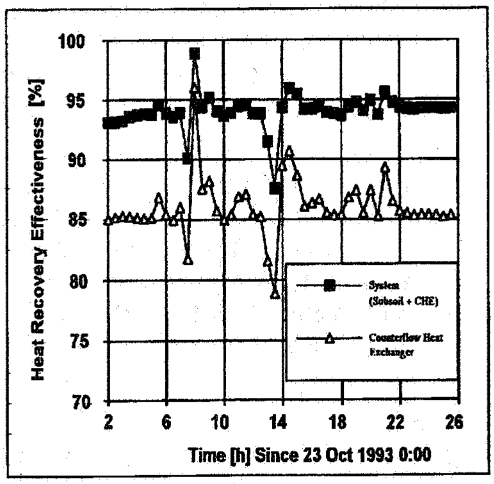

Fig. 5: Measured heat recovery effectiveness of the ventilation system (CHE: Counterflow Heat Exchanger).

5.1 Result: CO_2 Concentration

The level of CO_2 concentration is a good indicator for man made emissions in indoor air of residential buildings. CO_2 levels are continually measured for the living area in the ground floors and the living rooms in the upper floors, respectively. The sensors of infrared absorption type are calibrated regularly by test gas mixtures, the error of results amounts to about $\pm$ 30 ppm.

The amount and the distribution of air flows are sufficent to keep the CO_2 levels below 1000 ppm. A comparison with Fig. 2 shows that the indoor air quality, especially in bedrooms in the upper floors, is much better with continuos ventilation by a mechanical system.

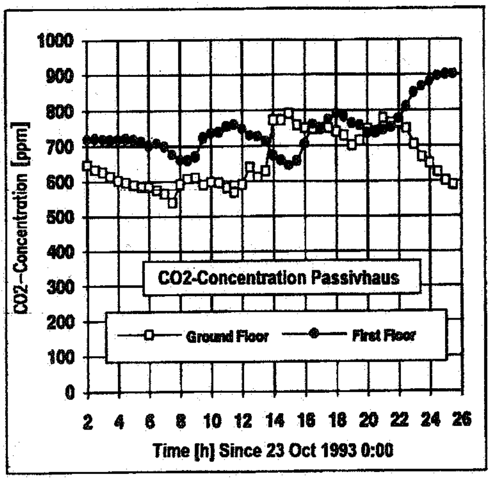

Fig. 6: Measured CO_2 concentrations.

5.2 Results: Relative Humidity

At room air temperatures between 18 and 23 °C, wich are typical for the Passivhouse during wintertime, the level of relative humidity is imperceptible for humans. Nevertheless, it is a crucial parameter for indoor air quality.

- In dry air (< 35 %r.h.) it is more likely that dust swirls up and electrostatic charging occurs.

- Relative humidity > 60 % improves the living conditions for mites, one of the most freqent occuring riscs for allergic reactions
- Higher humidity levels can lead to growth of mould (>65 %r.h. for some aspergillus species, > 80 % for cladosporium herbarum and penicillium species). This is not only a risk for the building structure, it is also an allergenic risk for the inhabitants and may also be the direct caus of infections.

Especially continually high relative humidities are hazardeous: "Keep the houses dry" /Kronvall 1988/ was one of the most important conclusions of the congress "Healthy Buildings" 1988 in Stockholm.

Fig. 7 shows the course of relative humidities at 23 October 1993 (Saturday), a typical day for the heating season. At relative humidities between 75 and 98 % in the outside air the relative humidities in the rooms with supply vents amounted to a nearly constant level of about 50 %, in kitchen and bathrooms the levels stayed between 52 and 55 %. A small rise, caused by showers, is visible in the bathroom in the morning. The removal of humidity takes a few hours, but the storage capacity by sorption of unsealed surfaces is sufficient to limit the peaks. On average surfaces and room air also in bathroom and kitchen stay dry. Relative humidities above 60 % inside the Passivhaus were only noticed during muggy days in summer.

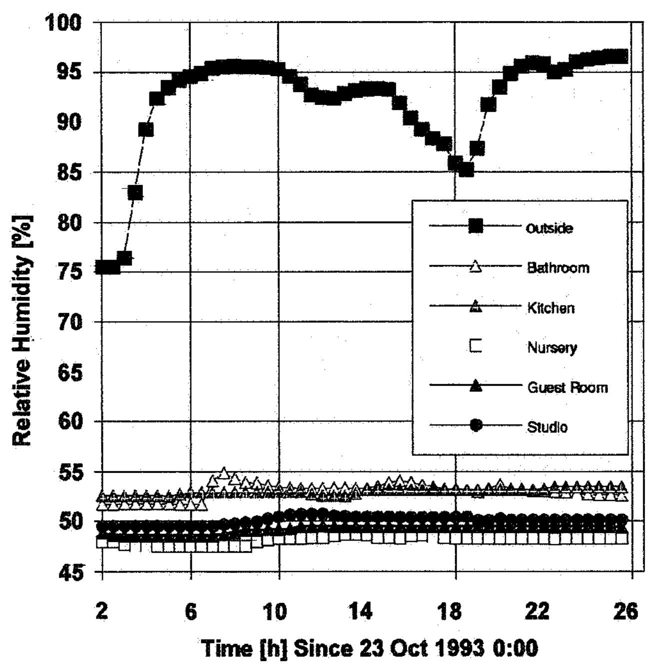

Fig. 7: Measured Levels of Relative Humidity in the Passivhaus".

Considering the detected levels of relative humidities there is no condensation on any surface, even the perimeter of the window panes stay dry. Taking into account the diffusion properties of the thermal envelope there is also no condensation in any place of the building structure.

5.3 Results: Radon

The noble gas radon and its daughters are second to tobacco smoke the most frequent reason for indoor caused cancer. The WHO recommends /WHO 1987/ concentrations below 100 Bq/m^3 EER for new buildings. Each of the four units of the Passivhaus were tested 5 times by char coal dosimetry over a period of 3 days: The measured levels were all below 50 Bq/m^3. Even more meaningfull results are delivered by active dosimetry, done from 11. to 18. February 1994. The mean activity levels inside the living rooms were 15 to 25 Bq/m^3 EER. Compared to the average value (median) in the region of Darmstadt (45 Bq/m^3), the radon concentration in the Passivhaus is low. The existing small activity is due to exhalations from building materials, since the floor to the basement is almost airtight (demonstrated by pressurisation), infiltration is minimal (demonstrated by tracer gas measurements) and the supply air has a much lower activity.

5.4 Results: Volatile Organic Compounds

Each of the 4 units and outside air were tested on formaldehyde during 4 sessions.

Fig. 8 shows the course of the accumulated concentrations of chlorinated compounds, polynuclear aromatic hydrcarbons (PAH), alkane, terpene, formaldehyde and other compounds. The average of all 16 measurements of room air concentrations of these compounds, except of terpene, are far below 90 % values of the /BGA/ study for german residential buildings.

In the beginning some hydrocarbon levels were found to exceed the BGA 90% values (styrene up to 30 $\mu g/m^3$, ethylbenzol up to 53 $\mu g/m^3$). For both compounds, there is a high probability to escape from the insulation material polystyrene on the outside of the walls. The concentrations never reached serious levels (/WHO/ guidelines believe a level of 800 $\mu g/m^3$ to cause no adverse health effects, the odour detection threshold amounts to 70 $\mu g/m^3$). The levels gradually decreased to the detection threshold of 3 $\mu g/m^3$.

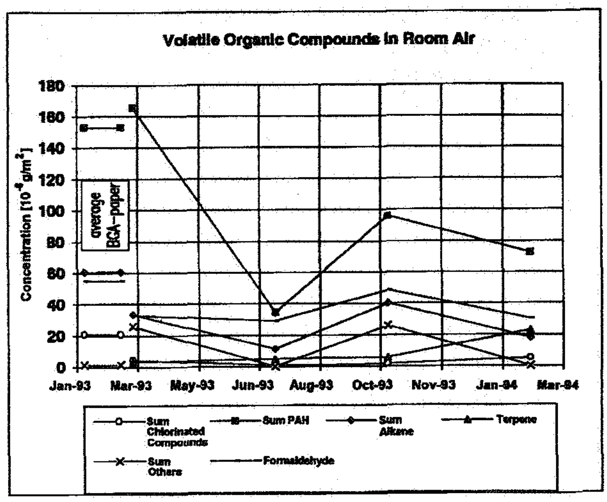

Fig. 8: Summed up Concentrations of Volatile Organic Compounds in Room Air.

The average formaldehyde level amounts to 34 $\mu g/m^3$ (90% BGA value 55 $\mu g/m^3$). Even the highest measured peak value is below the BGA threshold value (120 $\mu g/m^3$), but slightly higher than the WHO recommendation (60 $\mu g/m^3$).

5.5 Results: Suspended Dust

An analysis of mass and number distribution of particles with diameters between 0.5 and 100 μm was performed as well as a qualitative identification.

Concentrations of suspended dust in the rooms were in the range between 18 and 48 $\mu g/m^3$ not far away from the levels of outdoor air (16 to 51 $\mu g/m^3$) wich are all normal concentrations in residential buildings without specific pollution. To some extent there is a deposition in the filters of the ventilation system visible (inside about $4 \cdot 10^6$ particles, outside about $7 \cdot 10^6$ particles). The qualitative identification shows a ratio of organic to anorganic particles of 10 to 100. Manmade mineral fibres were only found at times and occasionally with a indoor maximum of 180 fibres/m^3 at outdoor maximum concentration of 510 fibres/m^3. These are commonly found concentrations, a significant contamination by fibres of the rockwool insulation (roof) is not present. None of the measurements at supply air vents showed mineral fibres.

In the building, no asbestos containig material was used, nevertheless at 2 of 14 tests one asbestos fibre per sample was detected (calculated concentration 50 fibres/m^3). These fibres presumably come from the brakes of the trains at the nearby railway lines.

Conspiciously were pillow shaped particles (2000 to 6000 particles/m^3) with diameters of about 10 μm wich stem from PE-Filters in the heat recovery unit. These filters were replaced by types without particle emission.

5.6 Results: Microbiological Tests

Under everyday conditions a 2 level Andersen-Impaktor was used to test the concentration of airborne germs and spores, the volume of sampled air was 100 to 200 l. The tests were performed 6 times in 2 to 4 of the units. The samples were taken from the living rooms, outside air, and partially also at supply air vents.

5.6.1 Spores

Outdoor concentrations show the expected variation in correlation with the seasons: a maximum during summer (July 1993 2988 KBE/m^3) and lower values in the range of 20 and 630 KBE/m^3 during the other seasons, average concentration amounts to 646 KBE/m^3. 20 of 24 samples of indoor concentrations show very low values of 150 KBE/m^3 or less, higher values occur during summer (with opened windows) at two of the samples (320 and 521 KBE/m^3) and two values from 20 January 1993 (360 and 453 KBE/m^3). The reason for the last two values were afterward identified in mildew covered organic waste and fruits. The average concentration of spores over all 24 samples amounts to 115 KBE/m^3, this is about 82 % below the outdoor concentration. Supply air concentrations normally are below the identification threshold of 5 KBE/m^3 with a maximum of 20 KBE/m^3. Samples of the test filter in the heat recovery unit showed spores only occasionally (maximum concentration 370 KBE/mg mass of the filter); this result agrees with the very low contamination of supply air.

5.6.2 Germs

Germ concentration varied during seasons and over the units between values below identification threshold and a maximum of 190 KBE/m^3, outdoor concentrations varied from 30 to 179 KBE/m^3. The contamination level of indoor air strongly dependends on the behaviour of the inhabitants. The measured concentrations in the Passivhaus can be classified as completly harmless.

5.7 Assessment of Indoor Air Quality

For the assessmment of the measurement results, sketched in chapters 5.1 to 5.6, a team of 5 experts was set up. The results of 5 reports and 3 expert meetings may be summarized as follows (proceedings will be published by IWU later this year):

- Repeated air quality mesurements in the Passivhaus showed comparatively low contamination. The building and ventilation concept of the Passivhaus meets the requirements of good indoor air quality.
- Measured CO_2 concentrations show that the ventilation system is able to control the existing indoor air emissions.
- The humidity level of indoor air stays within the recommended range. Due to the excellent insulation, there is no risk of condensation.
- Radon activity inside the Passsivhaus is very low.
- Concentration level of styrene started at slightly increased values of 30 $\mu g/m^3$ and decreased over the time to values about 3 $\mu g/m^3$. This can be considered as completly harmless.
- Different assessments were given to the measured formaldehyde levels. The average concentration of 34 $\mu g/m^3$ is smaller then the recommended /WHO/ limit of 60 $\mu g/m^3$, but one sample is slightly higher (70 $\mu g/m^3$).

- Qualitative and quantitative dust measurement results showed no significant contamination, especially of the type of man made mineral or asbestos fibres. The source of the pillow shaped PE particles could be removed by changing the test filter material.
- The measured concentrations of spores of 20 of 24 samples are very low (< 150 KBE/m^3). The four slightly higher values (up to 531 KBE/m^3) are caused by behavior of the inhabitants. The levels of germ concentration is harmless.
- Further microbiological measurements are planned to check, wether or not there is mould grow in the subsoil heat exchanger during warm and humid periods.

6. Conclusions

- All experts agree, that the indoor air contamination is low compared to other investigations. Therefore the ventilation concept proved to be sound.
- The measurements have shown that an average air flow rate of about 25 m^3/h per person fulfills the hygienic requirements for residential buildings, if the following conditions are true: defined interzonal air flow directions, possibilities for user adjustment of supply air distribution, and doubling of the air flow rate on demand; low emission concept for furnishing, building materials, household products etc.
- Efficient heat recovery systems (effectiveness about 80%) with low electricity demand are available but not yet standard on the market.
- The contribution of the subsoil heat exchanger to the reduction of ventilation losses (38%) is better than calculated during planning. Wether or not there is a risk of mould groth during warm periods in that heat exchanger has to be checked by further investigations.
- The automatic air quality control of the ventilation system works well, however, in combination with highly efficient heat recovery systems in residential buildings the reduction of ventilation losses is small compared to the expenditure.

References

/BGA/ Krause,C. et al.
"Occurence of volatile organic compounds in the air of 500 homes in the federal republic of Germany"
Proceedings of The 4th International Conference on Indoor Air Quality and Climate, Berlin, 17 - 21 August 1994, Volume 1 p 102 ff

/Blom 1990/ Blomsterberg, A.
"Ventilation ans airtightness in low-rise residential buildings - Analyses and Full-Scale Measurements"
Swedish Council for Building Research, D10:1990

/Feist 1993/ Feist, W.; Werner, J.
"Erste Meßergebnisse aus dem Passivhaus Darmstadt Kranichstein"
Gesundheitsingenieur Heft 5 Oktober 1993, p 240 ff

/Feist 1994/ Feist, W.; Werner,J.
"Passivhaus Darmstadt - Gesamtenergiekennwert < 32 kWh/(m^{2}a)"
Bundesbaublatt Heft 2 Februar 1994, p 106 ff

/Kronvall 1988/ Kronvall, J.
"Conference Highlights in Building Physics for Healthy Buildings"
in Healthy Buildings 1988, Vol. 4: Conclusions and Recommendations for Healthier Buildings, Swedish Council for Building Research, Stockholm D15:1991

/Pett 1858/
"Über den Luftwechsel in Wohngebäuden"
Literarisch-Artistische Anstalt der Cotta'schen Buchhandlung, München 1858

/SS 021551/
"Buildings - Determination of Airtightness" Standardiseringskommissionen i Sverige 1987

/WHO 1987/
"Air Quality Guidelines for Europe"
WHO Regional Office for Europe, WHO Regional Publications. European Series No. 23, Copenhagen 1987