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Low-energy Museum Storage Buildings: Climate, Energy Consumption and Air Quality

UMTS Research Project 2007-2011: Final Data Report

National Museum of Denmark
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Low-energy Museum Storage Buildings: Climate, Energy Consumption, and Air Quality

UMTS Research Project 2007-2011: Final Data Report

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Content

1. Introduction

This research project focussed on four modern storage facilities in Denmark, which are all similar in design, construction and size. The four buildings are purpose-built storage facilities, aimed at providing a high quality storage environment despite a low energy consumption rate for the climate control systems. Hereby we present data for indoor climate and air quality, energy consumption, and measurements of related physical building properties; e.g. air exchange rates.

From 2004-2007, the National Museum of Denmark implemented the Climate Notebook climate data management system for the monitoring of temperature and relative humidity (RH) in all of the museum's storage areas[1]. The storage facilities of Sydvestjyske Museer's storage building ('Ribe') and the Joint Storage Facility in Vejle ('Vejle') were also included in the project. These new purpose-built stores were constructed to provide a high-quality storage environment at a low energy consumption rate.

Both of the new stores are regulated toward a steady relative humidity set point (e.g., 50 % RH) while the temperature is allowed to vary over the year (no heating for basic storage environment, and a few degrees of wintertime 'conservation heating' for dry environments). The yearly temperature variation is typically on the order of 8-10 degrees; for example from 8 °C in winter up to 17 °C in summer. The desired indoor climate is achieved by the combination of a highly insulated building with a low air exchange rate, an un-insulated but heavy floor acting as a heat store, and air-conditioning by mechanical dehumidification; in some instances combined with a little winter heating.

As a continuation of the Climate Notebook project, the aspect of energy consumption also came under investigation. Since 2006, the energy consumption of the Vejle facility has been monitored, and since 2007 that in Ribe. In 2007, the National Museum of Denmark started up a new research project, supported by Danish UMTS research funds, on the energy consumption of low-energy museum storage buildings. Within this project, other physical parameters of the buildings were also documented, including air exchange rate, indoor air quality, and the ground temperature below and around the buildings. When the Joint Storage Facility for museums in Middle and East Jutland ('Randers') was opened in 2008, this building was also included in the monitoring project. From the National Museum of Denmark, a storage building (Hall P) from the Ørholm storage facility was included in the project ('Ørholm').

Besides the four main sites (Vejle, Ribe, Randers, Ørholm), the energy and climate data from other Danish storage facilities has been included for comparison, however, collected on a less intensive scale. These additional sites were:

[1] Reilly, J.M., Johnsen, J.S., and Jensen. L. Aa., 2007: Documenting and optimizing storage conditions at the National Museum of Denmark. In: *Museum Microclimates, Contributions to the Copenhagen conference, 19 - 23 November 2007*, National Museum of Denmark, pp. 123-128.

- The Music Museum (National Museum of DK): Storage room. Søborg, Copenhagen
- National Museum of DK: Temporary storage in former airplane hangars. Værløse Airfield
- The Arnamagnæan Collection: Manuscript archive. Uni. of Copenhagen - Amager Campus
- National Museum of DK: Storage facility (Building 9). Brede, Kgs. Lyngby
- The Royal Library: Book storage facility. University of Copenhagen - Amager Campus
- Iron Mountain: Paper document archival facility. Avedøre, Copenhagen
- Moesgaard Museum: Storage Hall ('Fjernmagasin'). Aarhus
- Danish Film Institute: Cool film archive for acetate materials. Glostrup, Copenhagen
- Danish Film Institute: Cold film archive for nitrate materials. St. Dyrehave, Hillerød
- Royal Danish Arsenal Museum: Storage rooms in former military bunker. Copenhagen area.

In this report, the climate and energy consumption data is summarized for each building, typically for a period of between two and four years of measurement. The energy consumptions of different sites are compared in relative terms, as kWh per cubic metre of storage space, per year ($kWh/m^3 \times$ year). The conservation quality of each storage location is quantified in terms of the rate of chemical decay in the given environment. This is quoted as the Time Weighted Preservation Index (TWPI).

For each of the four main sites, measurement of the air exchange rate has been carried out at least twice, and the concentration of selected air pollutants has been measured over several months.

For the four main sites annual data summaries are listed in tables and climate data is shown in graphs.

The findings from this research project have been published extensively in a number of journal papers and conference contributions. This report is primarily for collating all of the data in one document. For analysis and discussion of the results, the published articles should be consulted. Publications originating from this project are listed in Chapter 12.

We thank the management and staff at all of the institutions involved for help and permission to use the storage buildings as the subjects of this study.

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The project was carried out by Morten Ryhl-Svendsen, Lars Aasbjerg Jensen, Benny Bøhm, and Poul Klenz Larsen.

The authors sincerely thank independent consultant Tim Padfield, Devon, United Kingdom, for valuable discussions throughout the study. Tim Padfield also co-authored several of the project's publications.

Brede, December 20th, 2012:

Morten Ryhl-Svendsen
Senior scientist, PhD
Project leader

2. Summary

2.1 Climate and energy performance

The following factors were monitored in detail at the four main sites (Ribe, Vejle, Randers, Ørholm): storage climate, energy consumption for air-conditioning, and air quality (including air exchange rate). For a number of additional storage facilities these factors were documented on a less intensive scale. The methods used are described in detail in Chapter 11.

Table 2.1 summarizes the main trends for the indoor climate, its conservation quality, and the energy performance of each of the different storage buildings.

What can be derived from the data is that if a high conservation quality (high TWPI = low chemical reaction rate) is the aim, then it is especially important to avoid high summer temperature[2]. Only the storage buildings which were designed for an annual temperature profile of always <18 °C reached a TWPI above 100 (see Fig. 2.1).

From an energy consumption point of view, it is not surprising, that the un-heated buildings are the most economical buildings to run, as only summer dehumidification is necessary if the winter temperature is allowed to decrease when the outdoor temperature drops[3]. When relative humidity is the only controlled parameter, it is clear that the lower the RH set-point, the higher the energy consumption. Typically, to maintain 30% RH instead of 50% RH will take on the order of 3-4 times more energy due to the higher and more constant moisture load.

A building, which maintains a temperature profile close to that of outdoors (e.g. Værløse; 0-26 °C) appears to have an energy need higher than that of the modern low-energy buildings, where the annual temperature typically spans between 8-17 °C. This is due to a constant moisture load when at near-outdoor temperature conditions (outdoor RH is generally always high in Denmark) which makes year-round dehumidification necessary. For the modern low-energy buildings, there is typically very little dehumidification need in winter because of a slightly higher indoor temperature.

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[2] The conservation quality of an indoor environment can be expressed by the "preservation index" (PI). This index value expresses the expected "lifetime" for certain organic materials, if kept continuously in that environment (temperature and relative humidity). For a fluctuating climate the variations in PI over time can be integrated to a time-weighted PI value (TWPI). A high PI expresses a higher lifetime than a low PI. For example; the PI for constant 22 °C / 50% RH = 34; for 16 °C / 50% RH = 72, and for 12 °C / 50% RH = 121.
See also: Reilly, J.M., Nishimura, D.W., and Zinn, E., 1995: *New Tools for Preservation: Assessing Long-Term Environmental Effects on Library and Archives Collections*. Washington, DC: The Commission on Preservation and Access.

[3] The conservation heating versus dehumidification issue is discussed in: Ryhl-Svendsen et al, 2010: Does a standard temperature need to be constant? *Meddelelser om Konservering* 1/2010, pp. 13-20.

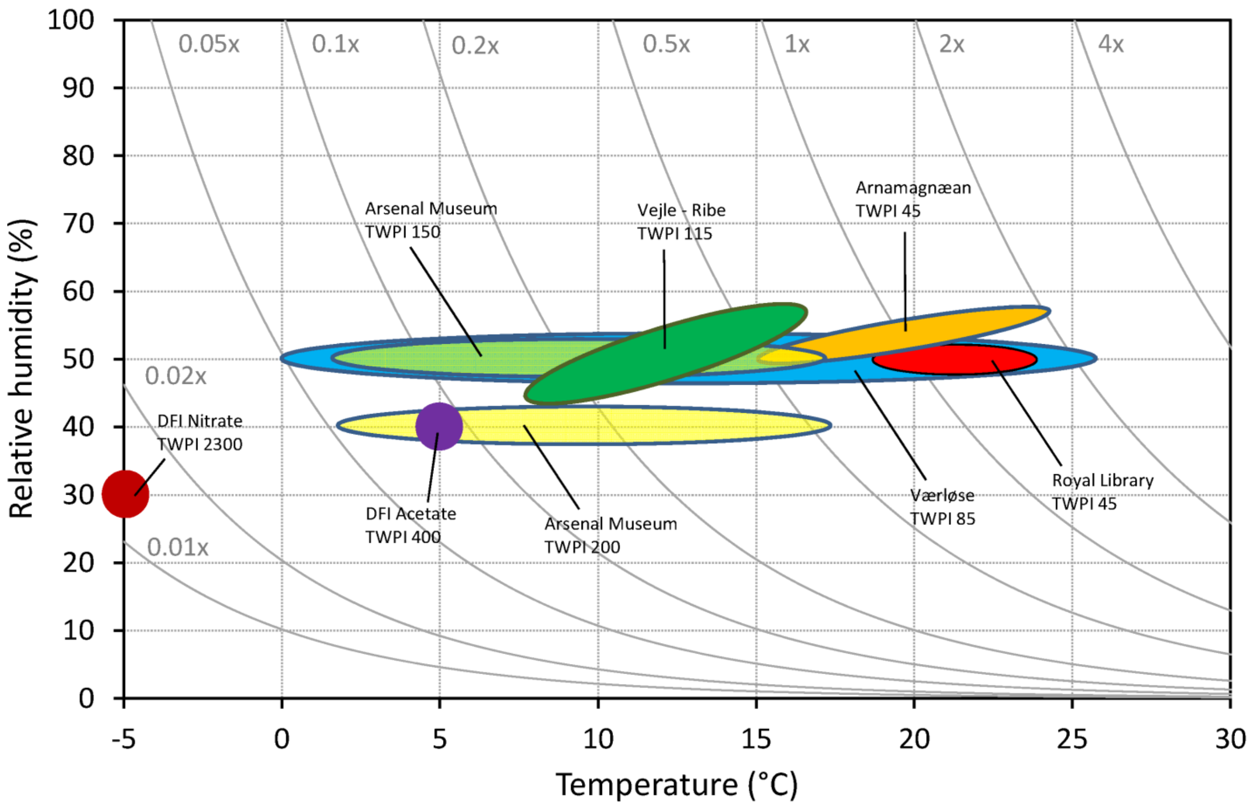

Fig. 2.1. Annual climate performance (temperature versus relative humidity) of a selection of storage facilities from this investigation. Superimposed in the diagram are so-called isoperm lines, which represent combinations of temperature and RH, which give an equal chemical reaction rate. The isoperm through 20 °C and 50% RH is set to "1" (see also Ryhl-Svendsen et al, 2010 (footnote 3)). The time-weighted PI is given for each building.

This underlines the benefits of the low-energy building design with a low-ventilated and thermally well-insulated superstructure, on a heavy and un-insulated floor and ground element, which can act as a heat store[4].

In theory, a building could be designed to maintain an annual temperature profile which always would result in 50% RH indoors. This could be achieved passively by solar heating; however, such a museum store has yet to be shown in reality. The disadvantage, however, would be a TWPI much lower than for the un-heated buildings in the style of the Vejle, Ribe and Randers buildings. Alternatively, on-site energy production by solar panels for running the dehumidifier could be a solution for a completely off-grid museum storage building[5].

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[4] See for example:

- Ryhl-Svendsen et al, 2011: Ultra-low-energy museum storage. *ICOM-CC 16th Triennial Conference*, Lisbon 19-23 September 2011, ICOM Committee for Conservation, 8 pp.
- Bøhm and Ryhl-Svendsen, 2011: Analysis of the thermal conditions in an unheated museum store in a temperate climate. On the thermal interaction of earth and store. *Energy and Buildings* 43, pp. 3337-3342.

[5] Ryhl-Svendsen et al, in press (2013): A museum storage building controlled by solar energy. *Climate for Collections: Standards and Uncertainties*, Doerner Institute, 7-9 November 2012, Munich.

It appears that from an energy point of view it will be most beneficial to design a building which passively maintains an average temperature near to that of outdoors, or a bit above, with a smaller amplitude in the annual variation. The annual outdoor temperature in Denmark would, for an environment kept at 50% RH, perform with a TWPI of about 140. This is shown in Fig. 2.2 together with the TWPI versus Energy Use performance of a large selection of storage facilities. The superimposed trend-line suggests how the energy penalty rapidly increases the more the climate specifications depart from the ambient temperature profile; e.g. by an increased demand for heating or cooling, or by strict requirements of a constant climate (less fluctuation allowance). It is however important to notice that only by maintaining a naturally cool or a mechanically controlled cold environment is it possible to achieve a TWPI higher than 100. For the environments, which aims for constancy at near normal room-temperature, the resulting TWPI will be lower than 50 despite the very stable and well-maintained climate. There may be good reasons for choosing a warm and constant storage temperature (consideration for the mechanical properties of special objects, or the comfort of people), however, it is clear that from a strictly chemical decay rate point of view the conservation quality of such environments is low.

2.2 Air quality

2.2.1 Air exchange rate

There is a fine agreement between the air exchange rate of the buildings and the indoor moisture load. The low-energy buildings had an exchange rate in the range of 0.3 – 0.6 per hour, with the Ribe building being the most airtight and the Ørholm building the leakiest. The modern buildings, except Ørholm, all had an air exchange rate of less than 1 per day.

2.2.2 External pollutants

A low air exchange with the ambient air will naturally lower the influx of external air pollutants, and the indoor-to-outdoor ratio (I/O) of such pollutants was low for all of the stores. Nitrogen dioxide was typically found indoors in concentrations of 3-4 ppb, which corresponded to a ratio of 0.25-0.30 of the ambient level. Ozone was typically found indoors in concentrations of 1 ppb, which corresponded to a ratio of 0.03 of the ambient level. Ammonia was found in varying levels indoors, between 5-10 ppb, and there was not any significant pattern with respect to the outdoor conditions (sometimes the level was higher indoors, sometimes higher outdoors).

2.2.3 Internal pollutants

Indoor generated pollutants were typically found in the highest concentrations during summer, which can be explained by an increase in emissions from materials when the temperature increases. At the stores in Vejle, Ribe and Randers, the organic acid concentrations were, however, low even in summer: ca. 5 ppb. At storage rooms which were very densely packed with wooden objects the summer levels could be considerably higher (on the order of 25 ppb in Værløse, 50 ppb at the Music Museum, and up to 100 ppb at Ørholm). Still, these levels are not subject to conservational concern.

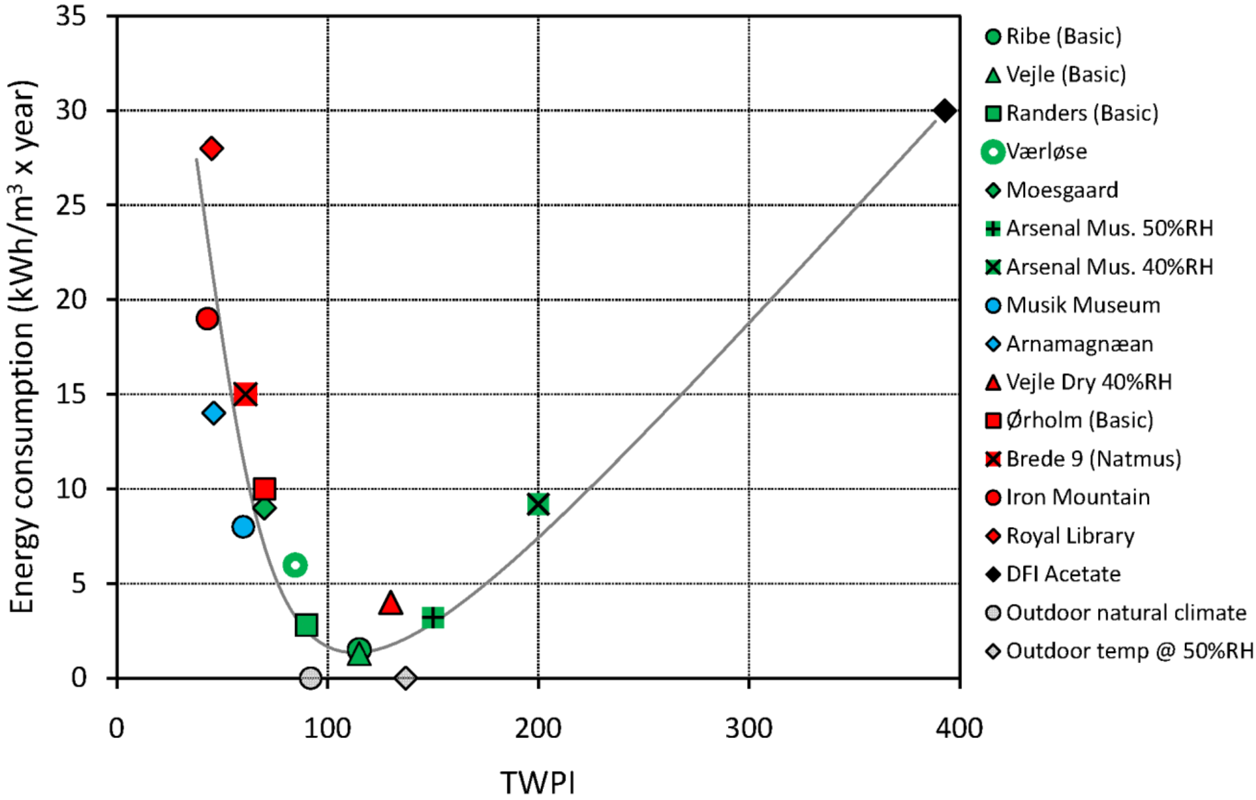


Fig. 2.2. TWPI versus Energy Use performance of the storage facilities:

- *The buildings marked in green are un-heated and dehumidified (Ribe, Vejle, Randers, Værløse, Moesgaard, and two locations at the Arsenal Museum).*
- *The buildings marked in blue have some degree of conservation heating in combination with a humidity buffering interior (Music Museum and Arnamagnæan Institute).*
- *The buildings marked in red have various degrees of HVAC with at least two of the control functions: humidification, de-humidification, heating, or cooling (Vejle Dry Store, Ørholm Hall P, Brede Building 9, Iron Mountain, Royal Library Stack 1).*
- *Danish Film Institute Acetate Store (marked in black) is constantly cooled and dehumidified.*

At zero energy use is shown the Danish outdoor climate (TWPI=92) as well as to which TWPI the outdoor temperature would perform if kept at a constant 50% RH (TWPI =140).

Further information on the storage buildings is found in Table 2.1

Table 2.1. Main trends for the indoor climate, its conservation quality, and the energy performance of each of the storage facilities (annual levels). The tabulated values are typical levels and do not represent one specific year of measurements.

Building	**Climate control**	**Tempera-ture [°C]**	**Relative Humidity [%]**	**TWPI [index]**	**Energy use, relative [kWh/m^{3}y]**
Ribe (basic storage)	Mechanical dehumidification. High thermal insulation. Set-point 50% RH	9-15	45-55	115	1.5
Vejle (basic storage)	Mechanical dehumidification. High thermal insulation. Set-point 50% RH	7-17	45-55	115	1.5
Vejle (dry storage)	Mechanical dehumidification + conservation heating. High thermal insulation. Set-point 40% RH & >10 °C	10-18	35-45	130	4
Randers (basic storage)	Mechanical dehumidification. High thermal insulation. Set-point 55% RH	8-19	50-60	90	3
Randers (dry storage)	Mechanical dehumidification. High thermal insulation. Set-point 30% RH	8-21	25-35	130	9
Ørholm Hall P	HVAC (not cooling). Set-point 55% RH	10-23	45-60	70	10 (estimated)
Music Museum, Søborg	Passive, buffered conservation heating. Aim 50% RH	8-26	45-55	60	8 (estimated)
Værløse Shelter	Mechanical dehumidification. Poor thermal insulation. Set-point 50% RH	0-26	45-55	85	6
Moesgaard Museum, external storage hall	Mechanical dehumidification. Moderate thermal insulation. Set-point 50% RH	7-24	35-65	70	9
Royal Danish Arsenal Museum, Bunker @ 50%RH	Mechanical dehumidification. Store is partly underground. Set-point 50% RH	2-17	45-55	150	3
Royal Danish Arsenal Museum, Bunker @ 40%RH	Mechanical dehumidification. Store is partly underground. Set-point 40% RH	2-17	35-45	200	9
National Museum, Brede 9	HVAC (not cooling). Set-point 50% RH	7-23	45-55	60	15
Royal Library (Stack 1)	HVAC Set-point 50% RH	18-23	45-55	45	28
Iron Mountain	HVAC	16-25	50-60	45	15 (estimated)
Arnamagnæan Institute	Buffered conservation heating with mechanical ventilation. Set-point 50% RH	15-24	50-55	45	14 (estimated)
Danish Film Institute (Acetate archive)	HVAC Set-point 40% RH	5	35-45	400	30
Danish Film Institute (Nitrate archive)	HVAC Set-point 30% RH	-5	25-35	2300	250

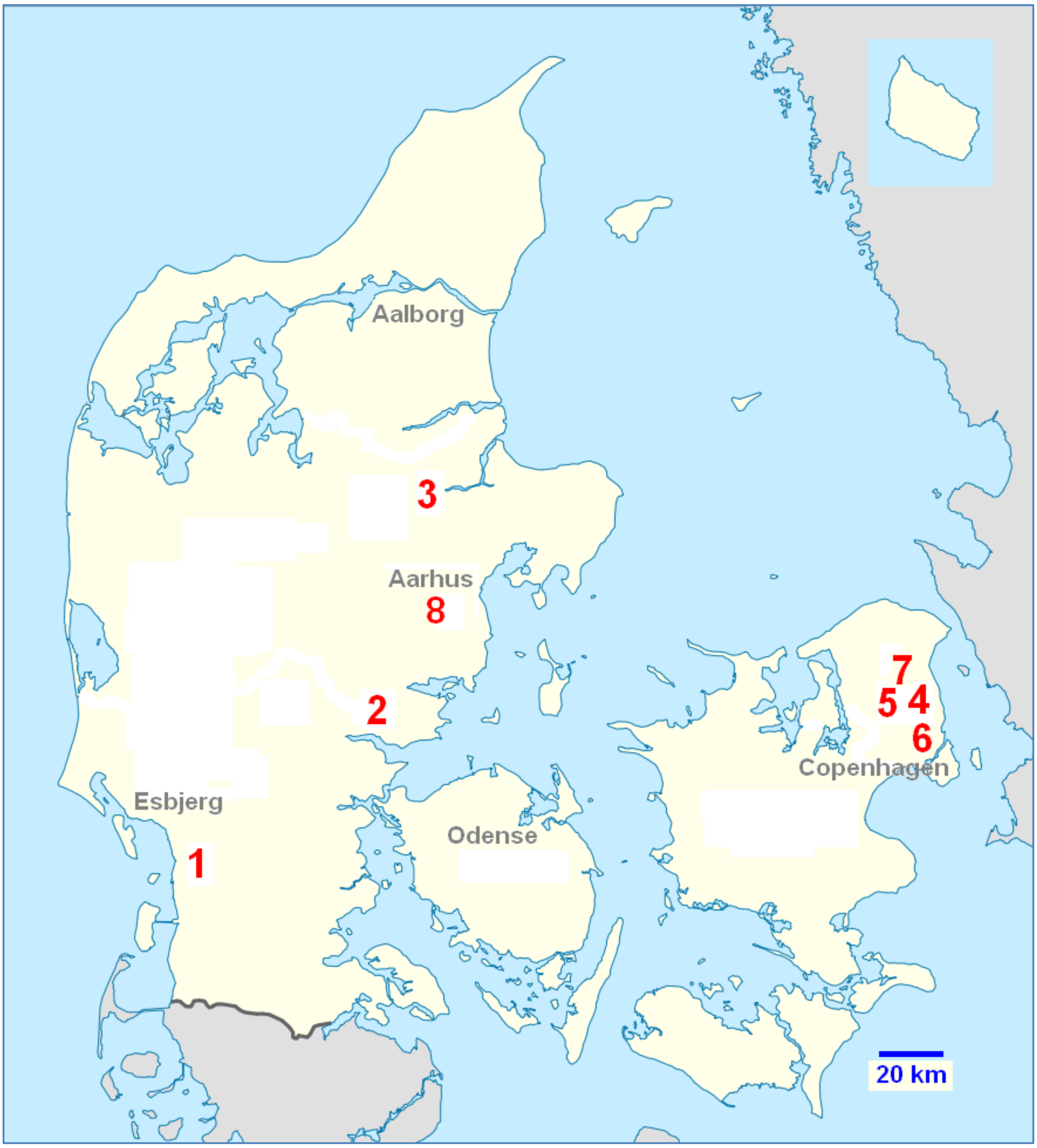


Fig. 2.3. Map of Denmark (source: Wikipedia) with the location of the storage facilities:

(1) Ribe
(2) Vejle
(3) Randers
(4) National Museum facilities: Ørholm & Brede
(5) Værløse
(6) Central and greater Copenhagen area: Arnamagnæan Institure; Royal Library; Royal Danish Arsenal Museum; Iron Mountain; Music Museum; Danish Film Institute - Acetate Archive
(7) Danish Film Institute - Nitrate Achive
(8) Moesgaard Museum

3. Climate and energy, main sites: Ribe storage building

Fig. 3.1. The storage building in Ribe.

3.1 General information

The Sønderjyske Museer's storage building is located Ørstedvej 46, DK-6760 Ribe.

The facility consists of one large building which houses a large storage room (volume 6200 m^3) providing a basic storage climate (about 50% RH) and a smaller (volume 290 m^3) storage room providing a dry storage environment (<40% RH). At the one end of the building is a storage depot for excavation equipment, etc. (not collection items), which is not climate controlled. Diverse staff facilities (office, kitchen, workshop) are located at the other end of the building along with an area for receiving goods and museum objects, including an inspection room. This part of the building is heated in winter for the staff's comfort. A large freezer for pest eradication, and the ventilation and climate control systems are also located at this end of the building.

The large basic climate store was 994 m^2 with 6.2 m height, and mainly equipped with compact shelves of full height. The smaller dry climate storage room was 99 m^2 with a height of 2.9 m.

The building is a purpose built museum store, which was constructed and taken into use in 2006. Storage rooms were empty during the first year of measurements, and from then on gradually filled.

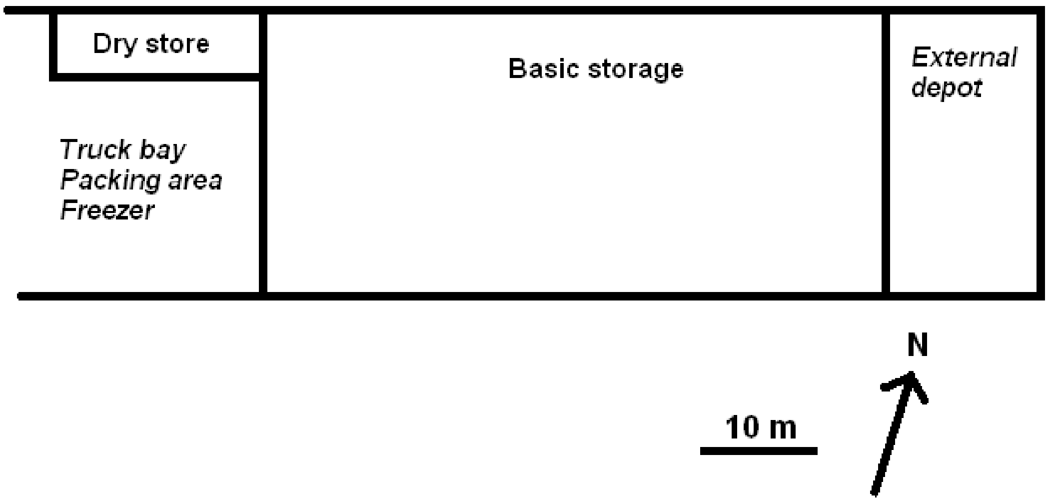


Fig. 3.2. Floor plan (approximately to scale) of the storage areas. The dry storage area is located on the second floor.

Fig. 3.3. Aerial photo of the Ribe storage building (in centre). Source: Google Maps.

3.2 Construction and insulation

The walls of the storage rooms are constructed as (from inside to outside): Fired Moler-clay bricks (110 mm), air gap (10 mm), precast concrete elements (facades 200 mm/gable 150 mm lightweight concrete), mineral wool (250 mm), air gap (50 mm), Fired clay brick (110 mm). U-value: 0.12 W/m^2 K.

The roof is (from inside to outside): Ceiling board is cement bound wood wool boards (250 mm) with mineral wool (300 mm) on top. The roof construction is a ventilated pitched roof with overhang consisting of plywood (18 mm) and aluminium covering ('Riverclack'). U-value: 0.09 W/m^2 K.

The floor is (from inside out): Epoxy painted concrete (200 mm), gravel drainage layer (300 mm), earth. No thermal insulation. U-value: 0.37 W/m^2 K.

3.3 Climate control

Each storage room is equipped with a separate desiccant wheel dehumidifier (Munters MLT350), which together with a ventilation fan draws and blows air to and from the storage rooms in a closed circuit. The re-circulation of air is constant, while the dehumidifier only turns on when needed (when the RH is too high inside the storage room). The large basic climate storage room has a re-circulation rate of about 0.2 room volumes per hour (flow: 0.35 m^3/s). There is no mechanical intake of air.

There is no direct heating of the large basic storage room; however, some heat will transfer from the climate control system (e.g. from the heat drying of the desiccant), as well as some heat will leak through the wall from the adjacent staff facilities.

For the dry storage room there is a possibility for a heating by a hot-water radiator, but this has not been utilized since 2009. Before that the room was moderately heated in winter. Energy for heating has not been monitored. As for the basic storage room it must be assumed that some heat will leak through the wall from the adjacent staff facilities.

3.4 Climate: Yearly statistics

Table 3.1: Basic climate storage hall. Climate control set-point: 55% RH (-2008), 50% RH (2009-). No temperature set-point. The climate is graphed in Figs. 3.4-3.6.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption [kWh]	Energy Relative [kWh/m^3 y]	Remarks
2007	13 (11-16)	55 (51-61)	93	Not measured	Not measured	
2008	12 (9-16)	57 (48-69)	98	Dehum: 4909 Fan: 3040 Total: 7949	1.28	Fan energy calculated
2009	12 (9-17)	51 (48-54)	108	Dehum: 6760 Fan: 3031 Total: 9791	1.58	Fan energy calculated
2010	11 (8-15)	51 (47-56)	123	Dehum: 6269 Fan: 3031 Total: 9900	1.50	Fan energy calculated

Table 3.2: Dry climate storage room. Climate control set-point: <40% RH. The climate is graphed in Figs. 3.7-3.9.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2007	17 (14-21)	46 (30-62)	68	Not measured	Not measured	Low RH control not yet initiated. Moderate winter heating (not measured).
2008	17 (14-22)	38 (32-45)	80	Dehum + Fan: 666	2.32 (+ heating, not measured)	Moderate winter heating.
2009	17 (13-22)	37 (36-39)	82	Dehum + Fan: 391	1.36 (+ heating, not measured)	Moderate winter heating.
2010	17 (11-22)	36 (32-38)	88	Dehum + Fan: 294	1.03	Only dehumidification

Table 3.3. Temperature gradient [°C] in centre of basic climate storage room (floor to ceiling), as measured four times over one year.

Height above floor	1-2-2010 12:00	1-5-2010 12:00	1-8-2010 12:00	1-11-2010 12:00
5.7 m (0.5 m below ceiling)	8.9	11.4	15.3	12.9
3 m	8.9	11.1	15.1	12.9
1 m	9.2	11.1	14.8	12.9
Floor surface	9.6	10.9	14.2	12.9

3.5 Trends and episodes

3.5.1 Basic climate storage area

The annual temperature variation for the basic climate storage area is typically 9-16 °C with minor deviations from year to year (Table 3.1). The lowest temperature is reached around the end of February, or in March, and the highest temperature occurs in August (Figs. 3.4-3.6). There is a slight trend of a decreasing temperature level, of about one degree during the latest three years.

The RH is maintained at a very constant level by the dehumidifier. Until the end of 2008 the set-point for the basic climate store was 55% RH; however, from December 2008 and onwards it was adjusted to 50% RH. During 2010 the RH varied slightly, from 47% RH during winter to 55% RH at the peak of summer (Fig. 3.6).

On two occasions during 2008 the dehumidifier was turned off for a prolonged period of time (each time more than a month), during which the RH rose steadily toward the natural level as influenced by the ambient humidity. One occasion was in July, where the RH almost reached 70% (Fig. 3.4).

The indoor climate results in a time-weighted preservation index (TWPI) of about 100 or better. Due to the slight temperature decrease during 2009 and 2010, the TWPI increased to index 123 for 2010.

In 2009-2010 the energy consumed to maintain this indoor climate was 1.5 kWh per m^3 of storage space, of which about 70% was consumed by the dehumidifier and the rest by the ventilation fan. While the fan runs continuously, dehumidification mainly takes place during summer. During the months July and August the dehumidifier runs at maximum effect (2.05 kW) for several weeks at a time, while during the three months from mid-December 2009 – March 2010 the dehumidifier was not running at all. The accumulated energy usage is shown in Fig. 3.10.

The temperature gradient from the floor surface to just below the ceiling was monitored for 18 months in the centre of the basic climate storage hall. In Table 3.3 the temperature at four different heights is listed for one day in winter, spring, summer, and fall. The highest temperature difference (ceiling – floor) was measured on 03-07-2010: **+2.4 °C** (room air warmer than floor surface). The lowest temperature difference (ceiling – floor) was measured equally on, respectively, 20-12-2009, 03-01-2009, 04-01-2010, and 27-01-2010: **-1.1 °C** (room air colder than floor surface).

3.5.2 Dry climate storage area

The annual temperature variation for the dry storage area is typically 13-22 °C with minor deviations from year to year (Table 3.2). The lowest temperature is reached in January; however the temperature level is rather stable during the period December to March. The highest temperature occurs in July or August (Figs. 3.7-3.9).

The RH is maintained at a very constant level by the dehumidifier, at about 38% RH. During 2010 the RH varied slightly, from 31% RH during winter to 39% RH at the peak of summer (Fig. 3.9).

In 2008 the dehumidifier was turned off for about one week during June, during which the RH rose to about 45% (Fig. 3.7).

The indoor climate results in a time-weighted preservation index (TWPI) of about index 84.

The energy consumed to maintain this indoor climate was about 1.2 kWh/m^3y for 2009-2010, however, some additional indirect heating was provided by heat leaking from the ambient staff and work rooms, and for the first years a moderate winter heating was in use. The amount of this additional energy consumption has not been quantified. The accumulated electrical energy usage is shown in Fig. 3.10.

Although the need for dehumidification is still higher during summer than during winter, due to the lower RH set-point there is no period of the year at which dehumidification comes to a stop (Fig. 3.10).

3.6 Climate graphs

3.6.1 Basic climate storage area

Legend: Temperature (red) and relative humidity (blue)

Fig. 3.4. Ribe basic climate, 2008.

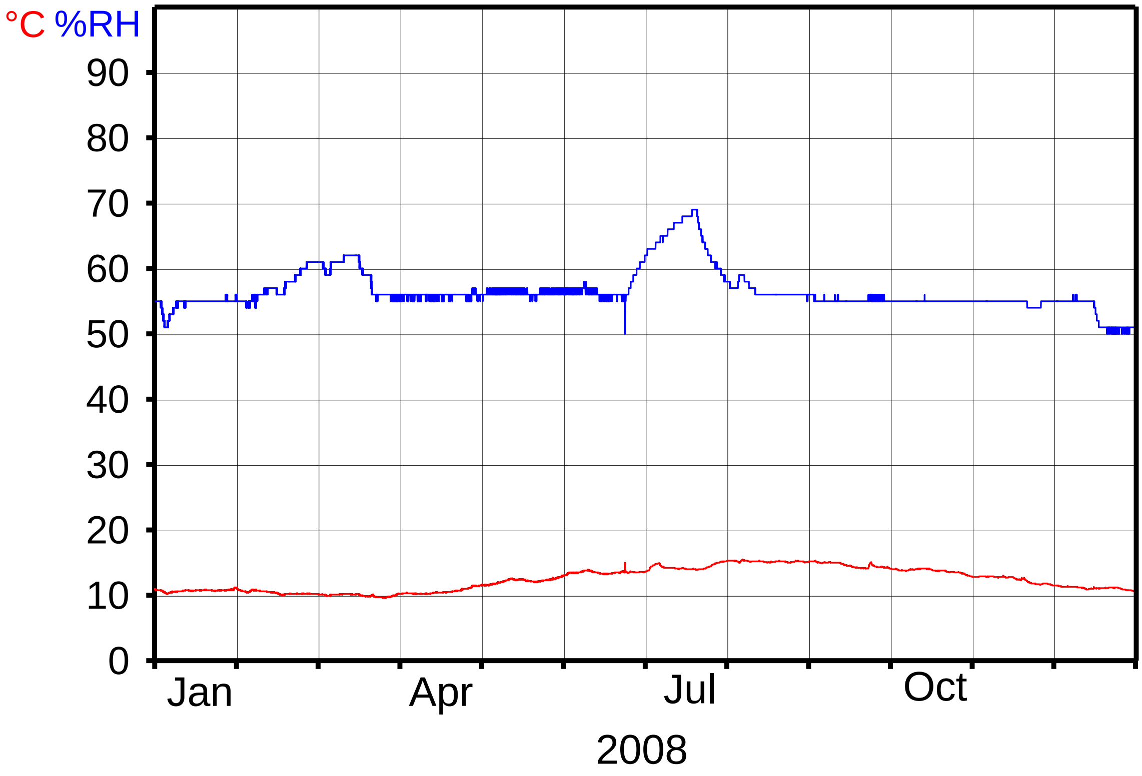


Fig. 3.5. Ribe basic climate, 2009.

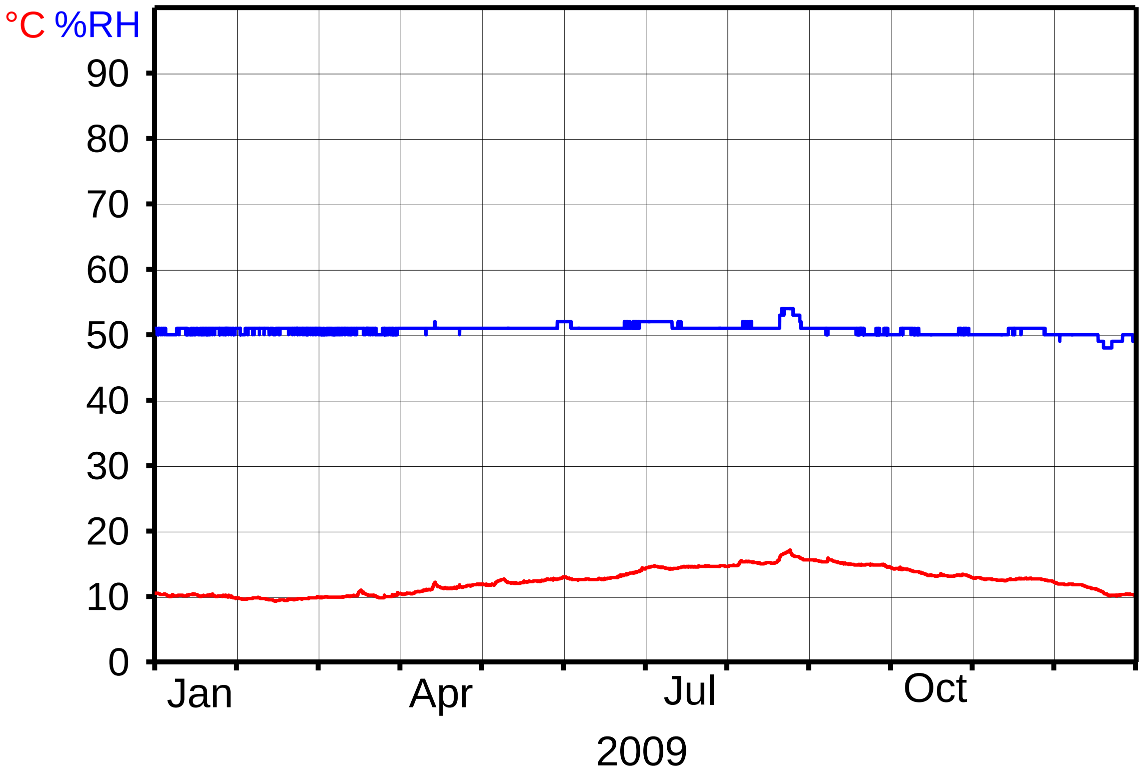
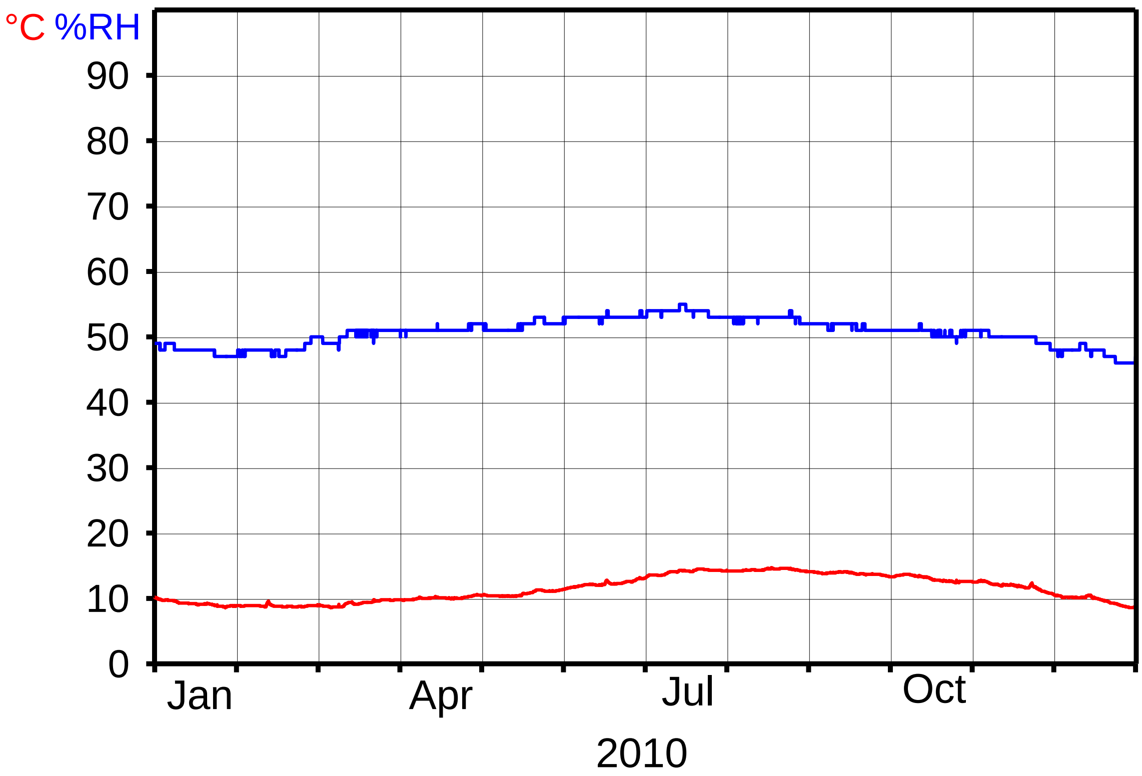


Fig. 3.6. Ribe basic climate, 2010.



3.6.2 Dry climate storage area

Fig. 3.7. Ribe dry climate, 2008.

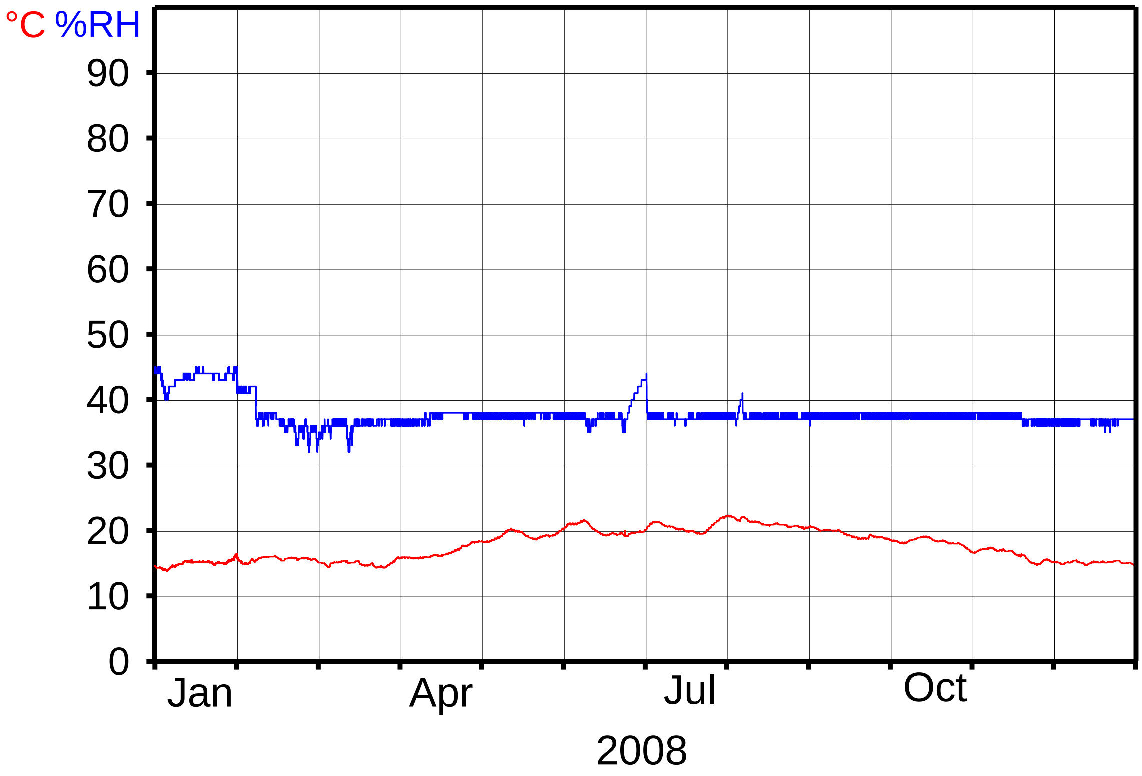


Fig. 3.8. Ribe dry climate, 2009.

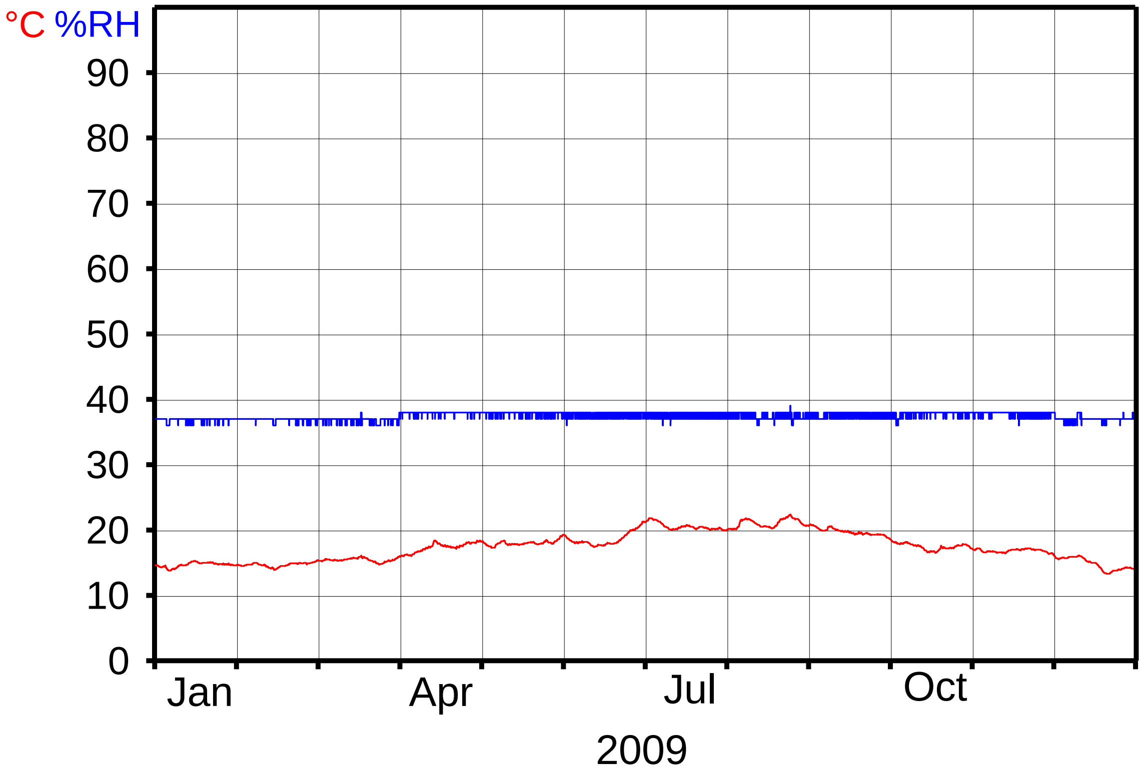
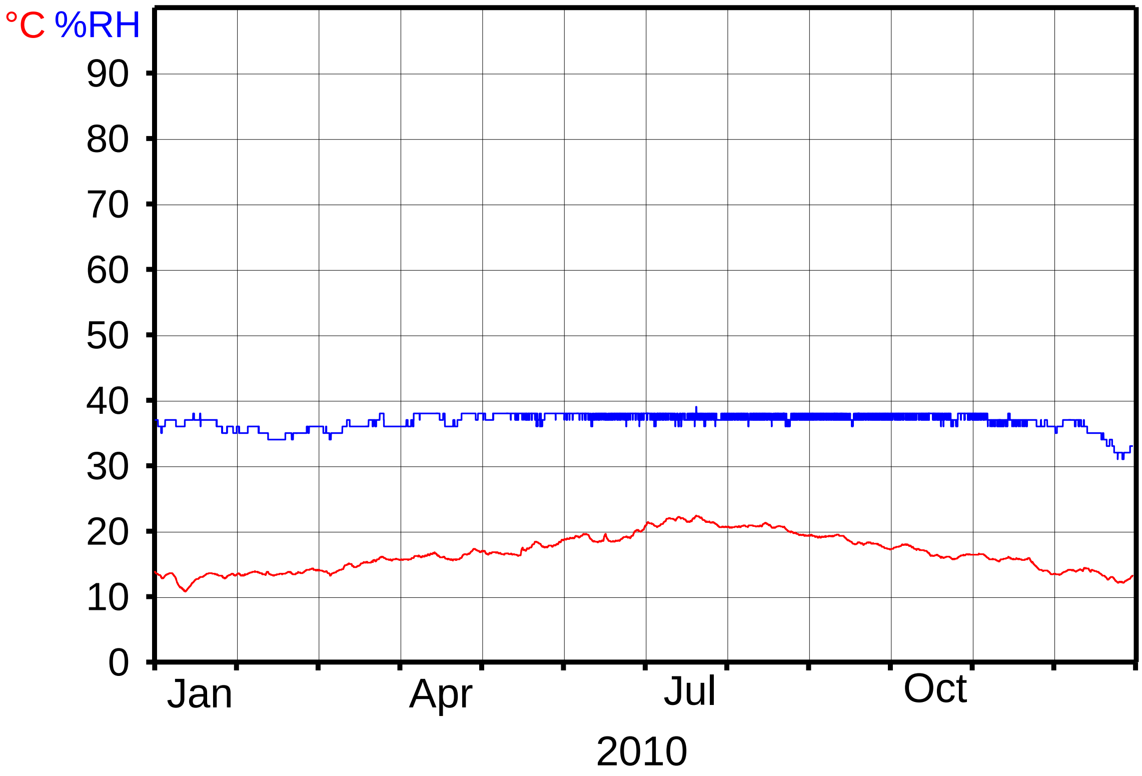


Fig. 3.9. Ribe dry climate, 2010.



3.7 Energy usage graph

Fig. 3.10. Accumulated energy consumption for dehumidifier and fan in basic climate storage area (purple) and dry climate storage area (green).

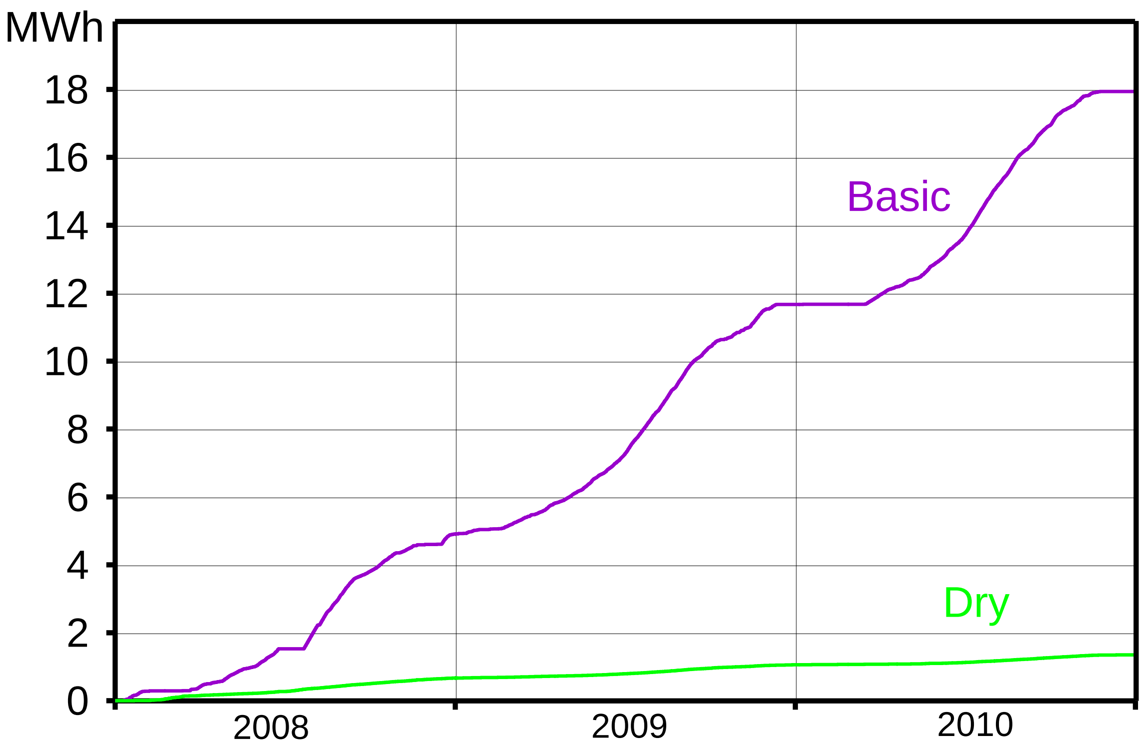


Fig. 3.11.
Top: Ribe basic climate storage hall (on mezzanine).
Bottom: compact shelves in dry climate storage room.

4. Climate and energy, main sites: Vejle storage building

Fig. 4.1. The Shared Storage Facility in Vejle

4.1 General information

The Shared Storage Facility's (Fælles Museumsmagasiner) storage building is located at Maribovej 10, DK-7100 Vejle.

The facility consists of one large building (approx 62 m x 24 m) which houses two large storage rooms (each area 1062 m^2 and volume 6570 m^3) and one smaller room (area 385 m^2, volume 2380 m^3). These three rooms provides a basic storage climate of about 50% RH. In addition to this, one smaller storage room of 385 m^2 (volume 2380 m^3) provides a dry storage environment (40% RH). All four storage rooms are clustered together with a hallway between the smaller and larger rooms (see floor plan in Fig.4.2). The hallway (248 m^2), which houses all of the ventilation equipment including dehumidifiers on a mezzanine floor, is also climatized to meet the basic storage climate of 50% RH. The total volume conditioned to a basic storage climate is 17,000 m^3. The halls have a free height of 6.3 m in the centre of the building, and are equipped with a combination of shelves on two floors (divided by a mezzanine) and open space areas for large objects.

Other facilities, including inspection rooms, a pest control freezer, and a small cold storage room for unstable plastic materials, are located in an adjacent building and connected through a double door climate lock. Those areas were not included in this analysis.

The entire facility is a purpose built museum store, constructed and taken into use in 2004. At the time of the measurements presented here the stores were already being gradually filled. In 2012, the storage facility was extended with a new building placed in direct contact to the east side of the existing store. The measurements in this report are all made before construction of the new building.

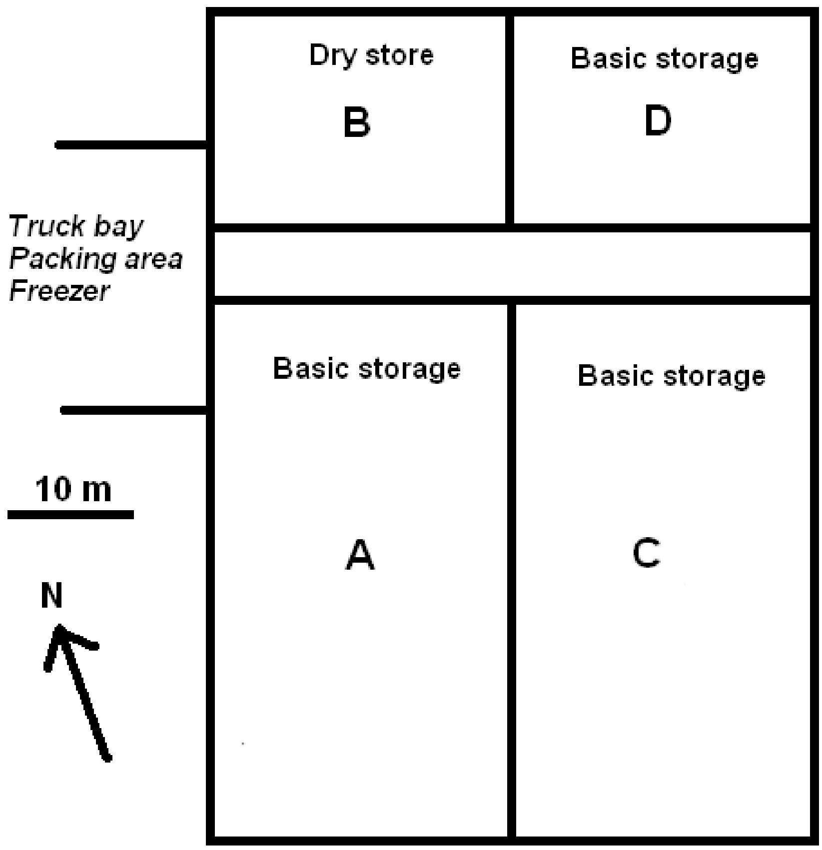


Fig. 4.2. Floor plan (approximately to scale) of storage areas.

Fig. 4.3. Aerial photo of the storage building (2011). Connected to the left is the Conservation Centre Vejle. In 2012 the storage facility was extended with a new building, placed in direct contact to the east side of the existing store (not on photo). Source: Google Maps.

4.2 Construction and insulation

The walls of the storage rooms are constructed as (from inside to outside): lightweight concrete (240 mm); mineral wool (250 mm); corrugated steel cladding (35 mm); silver metallic finish. U-value: 0.13 W/m^2 K.

The roof is (from inside to outside): profiled metal deck between double T girders; mineral wool (300 mm); 2 layers of bitumen roofing. The roof has a slight pitch. U-value: 0.12 W/m^2 K.

The floor is epoxy painted concrete (120 mm) on a gravel drainage layer (150 mm), and without thermal insulation. U-value: 0.41 W/m^2 K.

4.3 Climate control

Each climate zone (dry; basic) is equipped with a desiccant wheel dehumidifier (Munters MLT 800) and a ventilation fan, which draws and blows air to and from the storage rooms in a closed circuit. The re-circulation of air and the dehumidifier only run when needed (when the RH is too high inside the storage room). In that case, the air of the basic climate storage room can be re-circulated at a rate up to 0.45 room volumes per hour (7700 m^3 per sec). For the dry storage room, the re-circulation rate can be up to 0.33 room volumes per hour (800 m^3 per sec). There is no mechanical intake of outdoor air.

For normal use there is no direct heating of the large basic storage room; however, it is possible to initiate heating to avoid near-zero degrees temperatures. Some heat from the dehumidifiers and ventilation fans will transfer to the room air. The dry climate storage room is heated to about 10 °C in winter.

4.4 Climate: Yearly statistics

Table 4.1. Basic climate storage rooms A+B+D and corridor. Climate control set-point: 50% RH.
No temperature set-point (although heating may be utilized <7°C).
The climate is graphed in Figs. 4.4-4.7.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2007	12 (8-17)	51 (47-63)	109	Dehum: 21900 Fan: 4682 Total: 26582	1.56	
2008	12 (8-17)	51 (46-60)	110	Dehum: 21070 Fan: 4695 Total: 25765	1.51	Fan energy use based on 2007 measurement
2009	12 (7-17)	51 (47-60)	113	Dehum: 18070 Fan: 4682 Total: 22752	1.33	Fan energy use based on 2007 measurement
2010	11 (6-17)	52 (45-61)	122	Dehum: 14370 Fan: 4682 Total: 19052	1.12	Fan energy use based on 2007 measurement

Table 4.2: Dry climate storage room B. Climate control set-point: <40% RH. Temperature set-point: >10 °C. The climate is graphed in Figs. 4.8-4.11.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2007	13 (10-18)	42 (38-49)	130	Dehum: 4310 Heating: 2549 Total: 6859	2.88	
2008	13 (10-18)	40 (35-53)	138	Dehum: 4250 Heating: 4276 Total:8526	3.58	
2009	13 (10-18)	40 (36-48)	136	Dehum: 3700 Heating: 5807 Total: 9507	3.99	
2010	13 (10-17)	41 (37-47)	128	Dehum: 2780 Heating: 9900 Total: 12680	5.33	Heating energy use extra-polated from measurements Jan-0ct (7436 kWh)

Table 4.3. Temperature gradient [°C] floor to ceiling in centre of basic climate storage, Room C, as measured four times over one year.

Height above floor	1-2-2010 12:00	1-5-2010 12:00	1-8-2010 12:00	1-11-2010 12:00
5.8 m (0.5 m below ceiling)	6.4	9.8	15.4	11.5
3 m	6.8	10.0	15.3	11.6
1 m	6.9	9.7	14.9	11.8
Floor surface	6.9	9.1	14.0	11.4

4.5 Trends and episodes

4.5.1 Basic climate storage area

The annual temperature variation for the basic climate storage area is about 7-17 °C (Table 4.1). The lowest temperature is typically reached in February, and the highest temperature occurs in July or August (Figs. 4.4-4.7). There is a slight trend of an overall decreasing temperature level, of about one degree over the most recent year.

During one year the RH was maintained by the dehumidifier at a constant level just above 50% RH. There were a number of occasions where the system seems to have been down (due to maintenance or similar), sometimes up to one week and during which the RH rose to 60% or higher (Figs. 4.4-4.7).

The indoor climate resulted in a time-weighted preservation index (TWPI) of 122 in 2010.

The energy consumed to maintain this indoor climate was 1.2 kWh/m^{3}y for 2009-2010, of which about 77% was consumed by the dehumidifier and the rest by the ventilation fan. Dehumidification takes place mainly during summer, and less during winter. During the three months from mid-

December 2009 – March 2010 the dehumidifier was almost never on. The accumulated energy usage is shown in Fig. 4.13.

The temperature gradient from the floor surface to just below the ceiling was monitored for 18 months in the centre of the basic climate storage hall C. In Table 4.3 the temperature at four different heights is listed for one day in winter, spring, summer, and fall. The highest temperature difference (ceiling – floor) was measured on 10-07-2010: **+2.7 °C** (room air warmer than floor surface). The lowest temperature difference (ceiling – floor) was measured on 09-01-2010: **-1.5 °C** (room air colder than floor surface).

4.5.2 Dry climate storage area

The annual temperature variation for the dry climate storage area is between 10-18 °C (Table 4.2). The temperature level is rather stable at around 10 °C during the period from the beginning of December to the end of March due to heating. The highest temperature occurs in July or August (Figs. 4.8-4.11).

The RH is maintained at a constant level by the dehumidifier, at just above 40% RH.

On two occasions, in July 2008, and May 2010, the sensors were removed for calibration, which leaves a week-long “hole” in the data plots (Figs. 4.9 and 4.11).

The indoor climate results in a time-weighted preservation index (TWPI) of between about 130.

The energy consumed to maintain this indoor climate was about 4.7 kWh/m^{3}y for 2009-2010 (combined heating and dehumidification). There was an almost constant need for dehumidification all year, and heating to 10 °C during the winter months. In 2008 the energy used for heating and dehumidification of the dry storage was 50/50, while in 2009 heating consumed 64% of the total energy usage (Fig. 4.13-4.14).

4.6 Climate graphs

4.6.1 Basic climate storage area (Hall C)

Legend: Temperature (red) and relative humidity (blue)

Fig. 4.4. Vejle basic climate (Hall C), 2007.

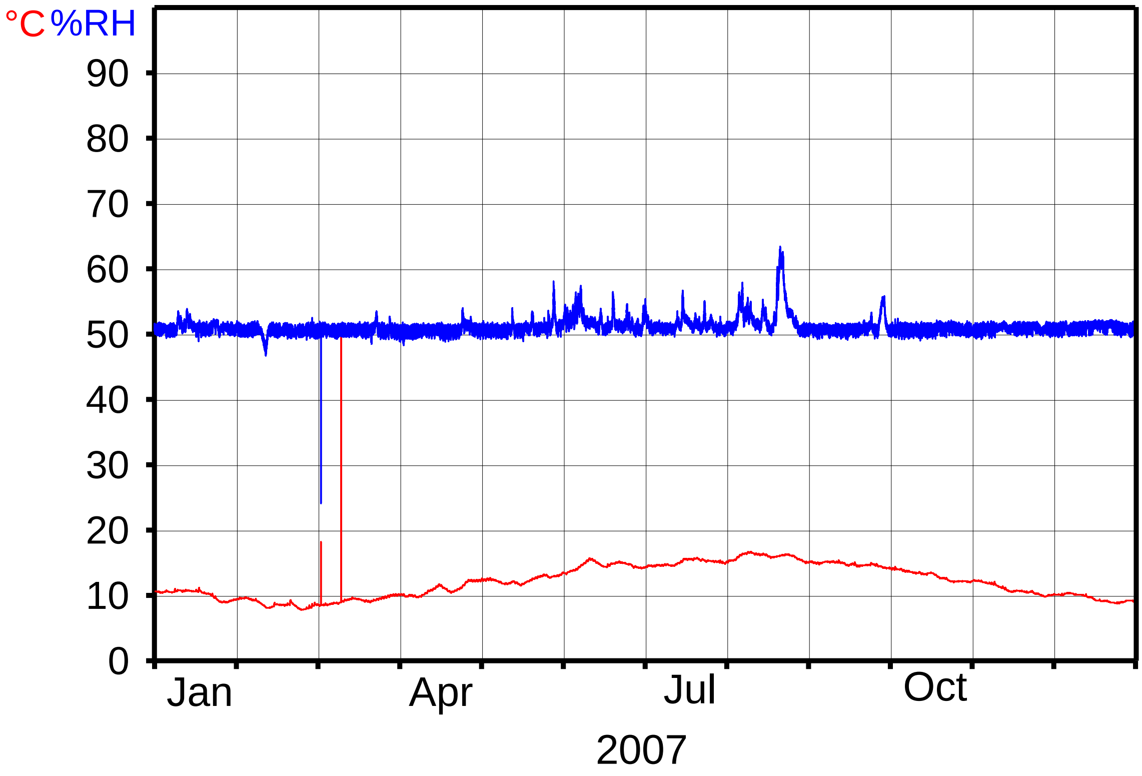


Fig. 4.5. Vejle basic climate (Hall C), 2008.

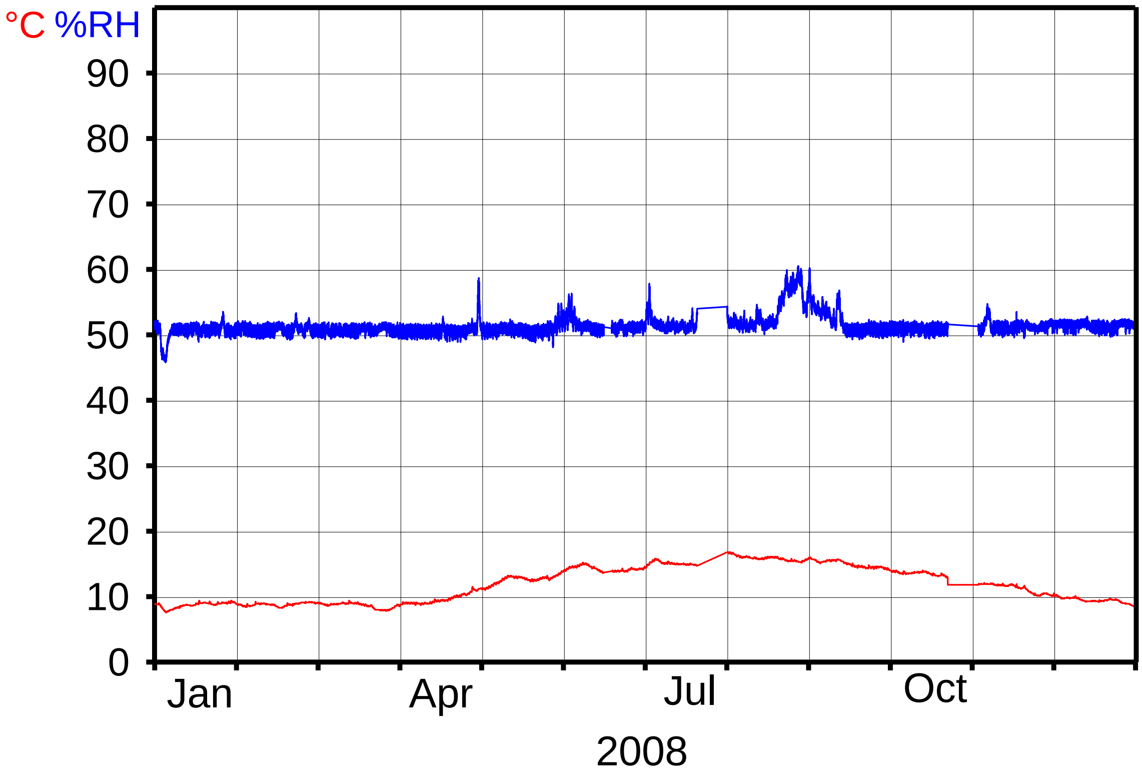


Fig. 4.6. Vejle basic climate (Hall C), 2009

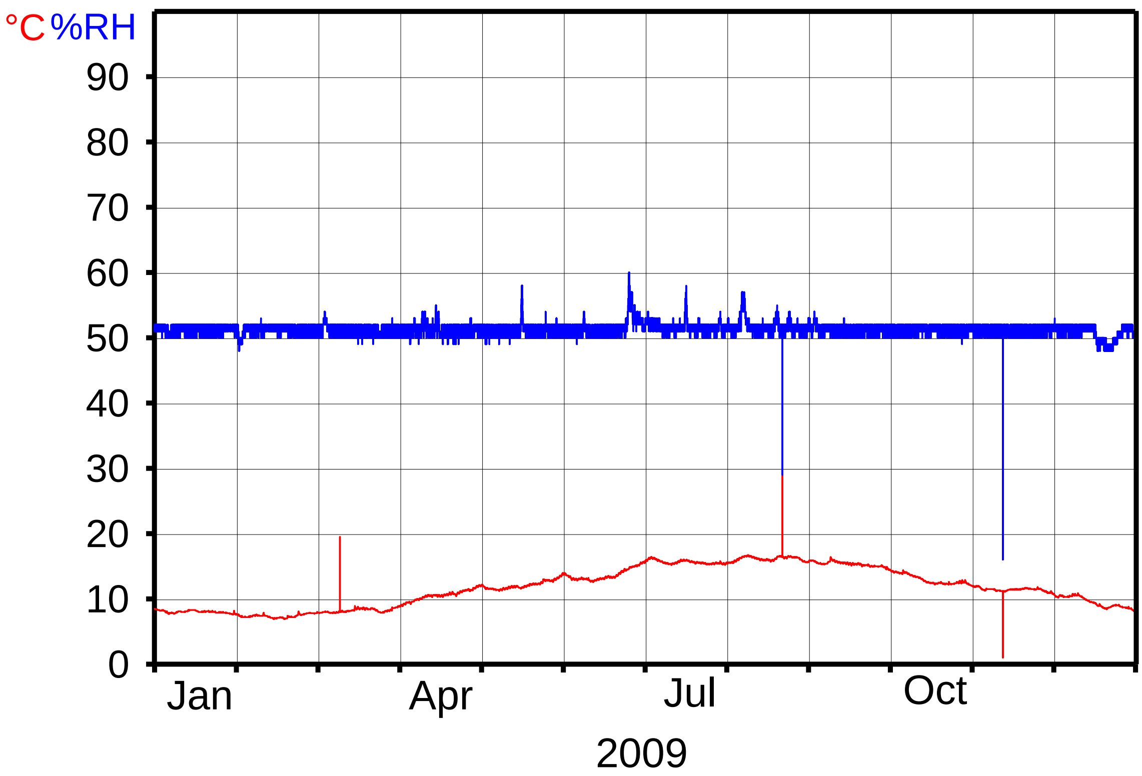
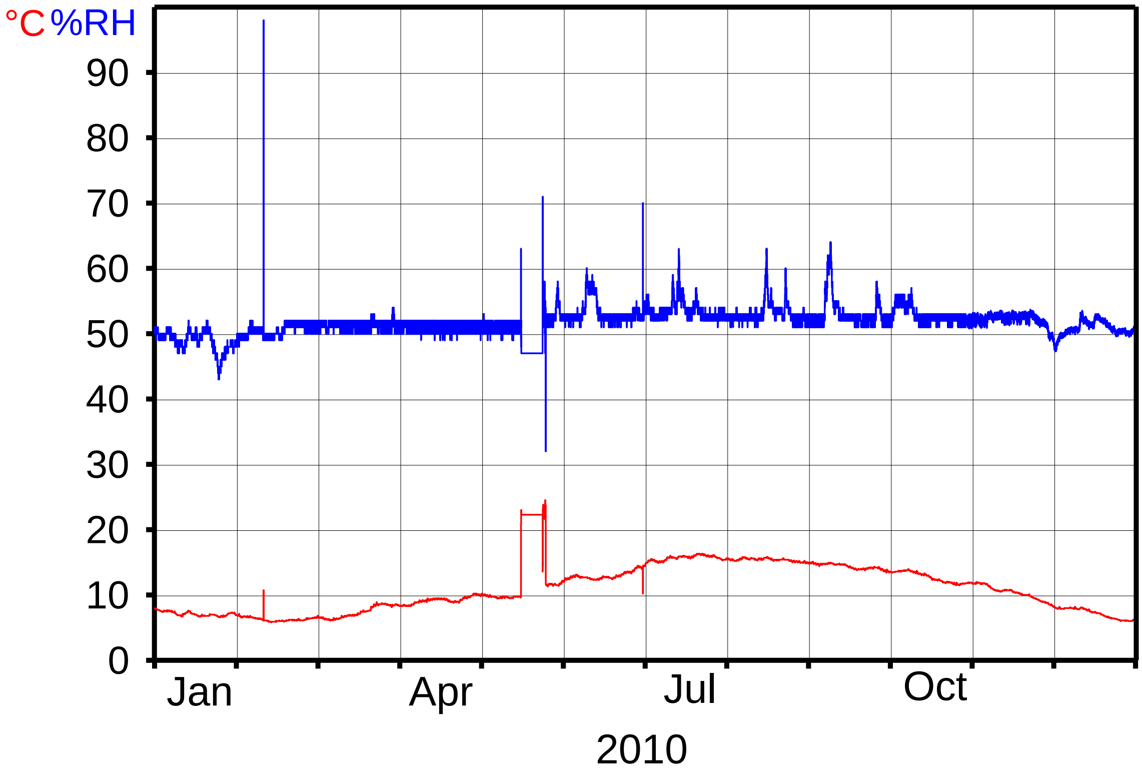


Fig. 4.7. Vejle basic climate (Hall C), 2010. Data is partly missing for May.



4.6.2 Dry climate storage area (Hall B)

Fig. 4.8. Vejle dry climate (Hall B), 2007

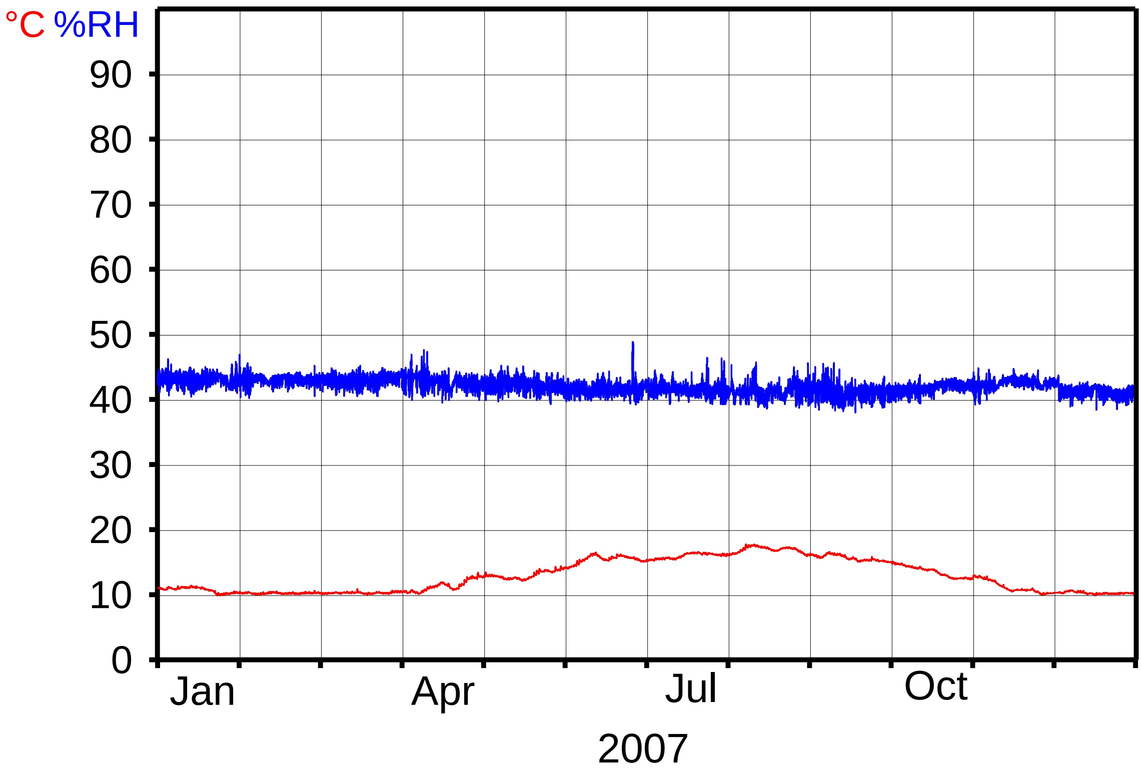


Fig. 4.9. Vejle dry climate (Hall B), 2008

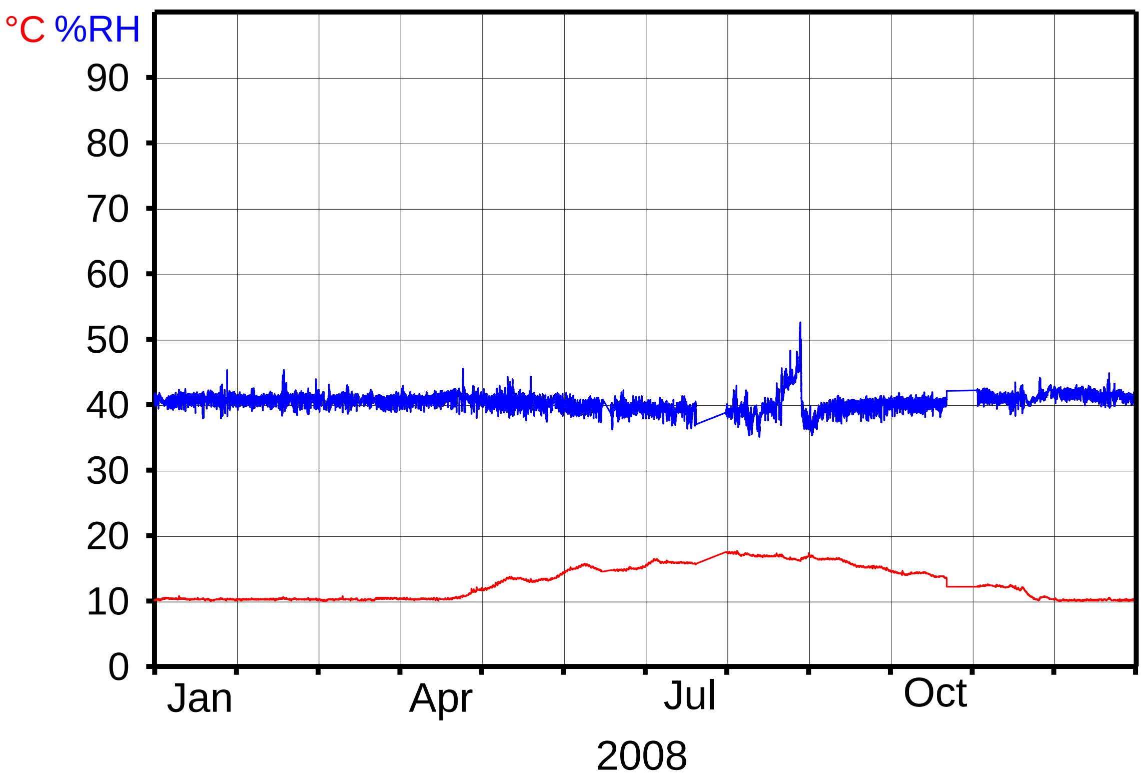


Fig. 4.10. Vejle dry climate (Hall B), 2009

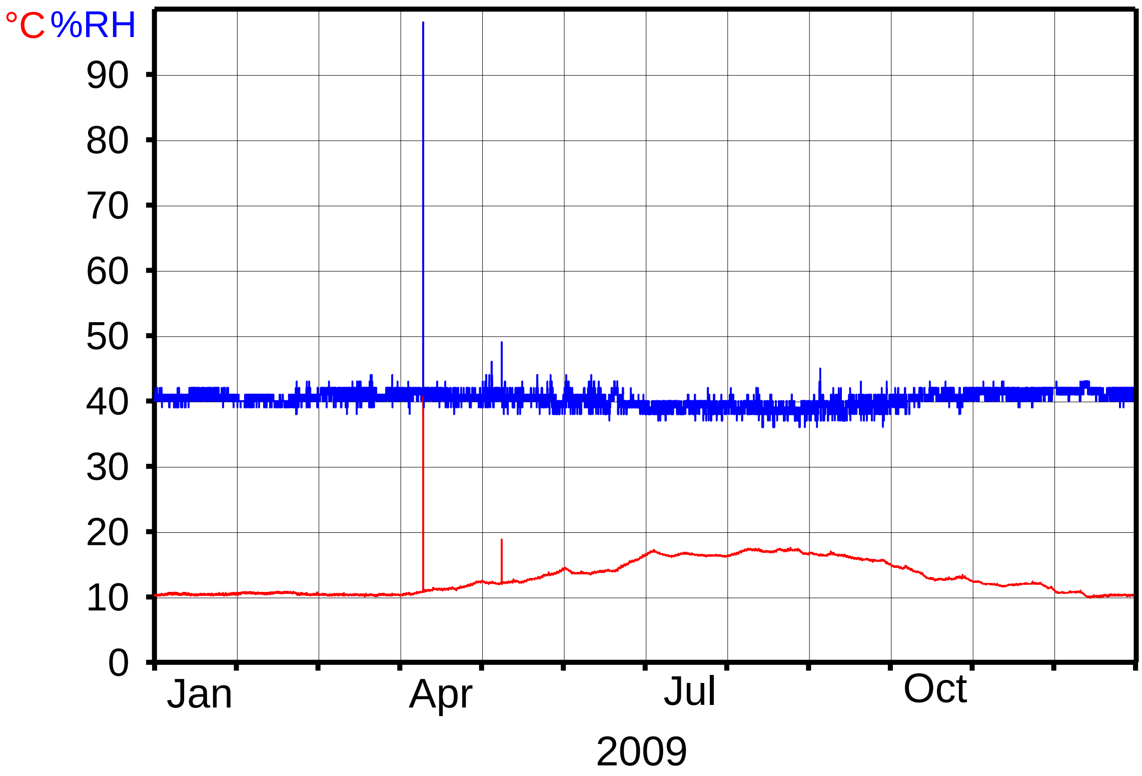
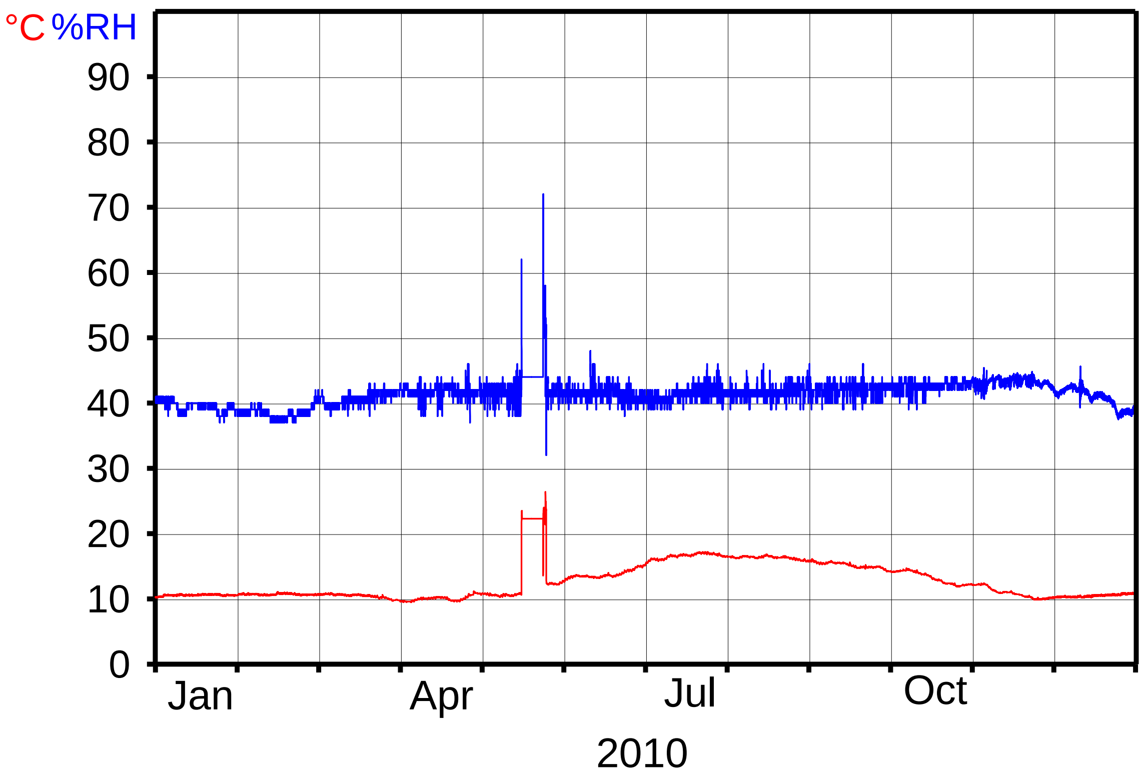


Fig. 4.11. Vejle dry climate (Hall B), 2010. Data is partly missing for May.



4.7 Energy usage graphs

Fig. 4.12. Accumulated energy consumption for dehumidifier and fan in basic climate storage area (purple) and dry climate storage area (green).

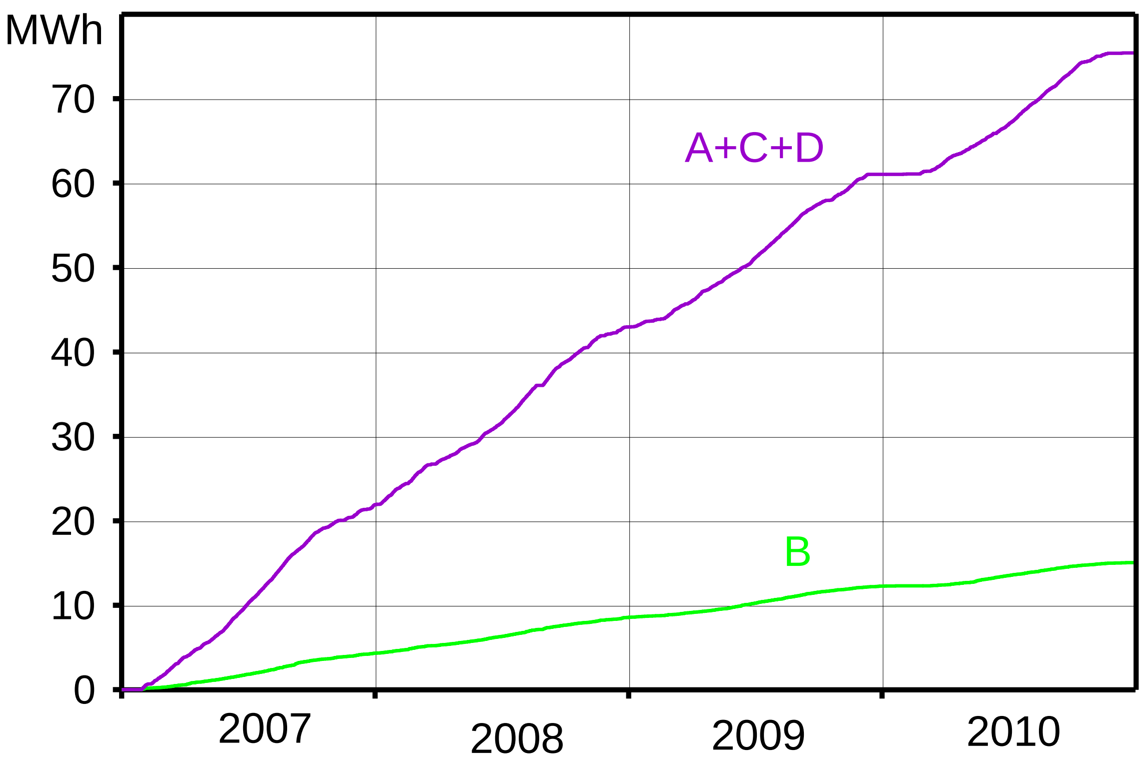
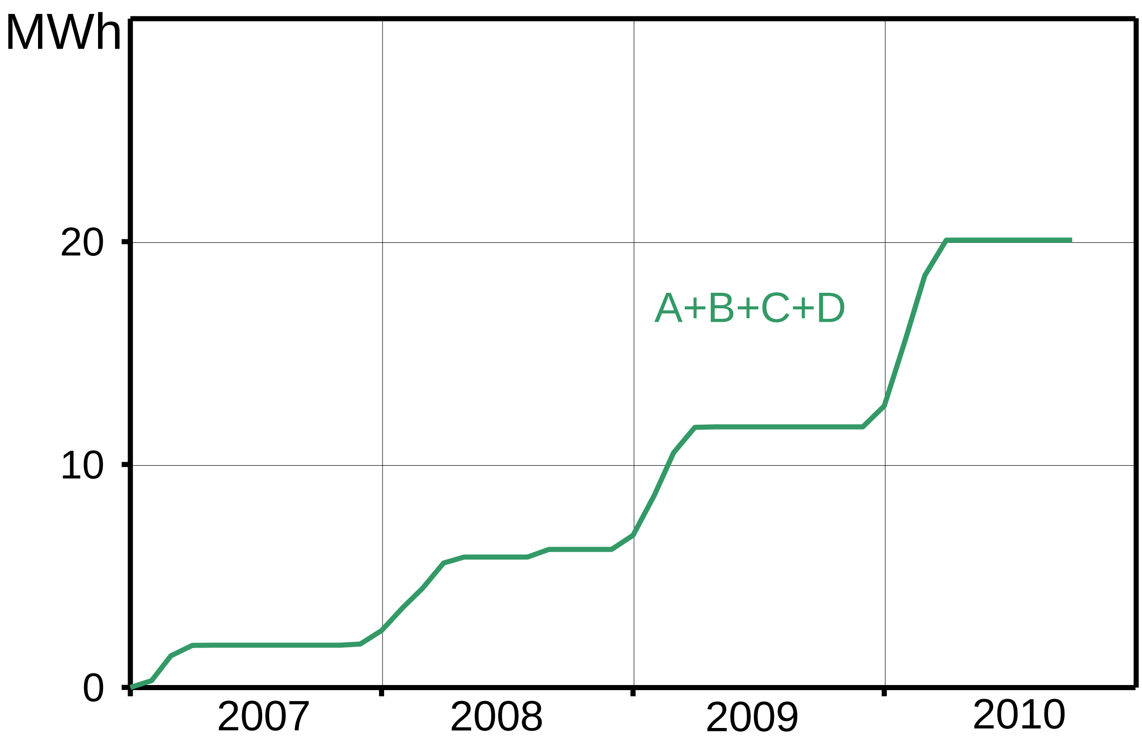


Fig. 4.13. Energy consumption for heating (accumulated). Only Hall B (dry storage area) is heated.



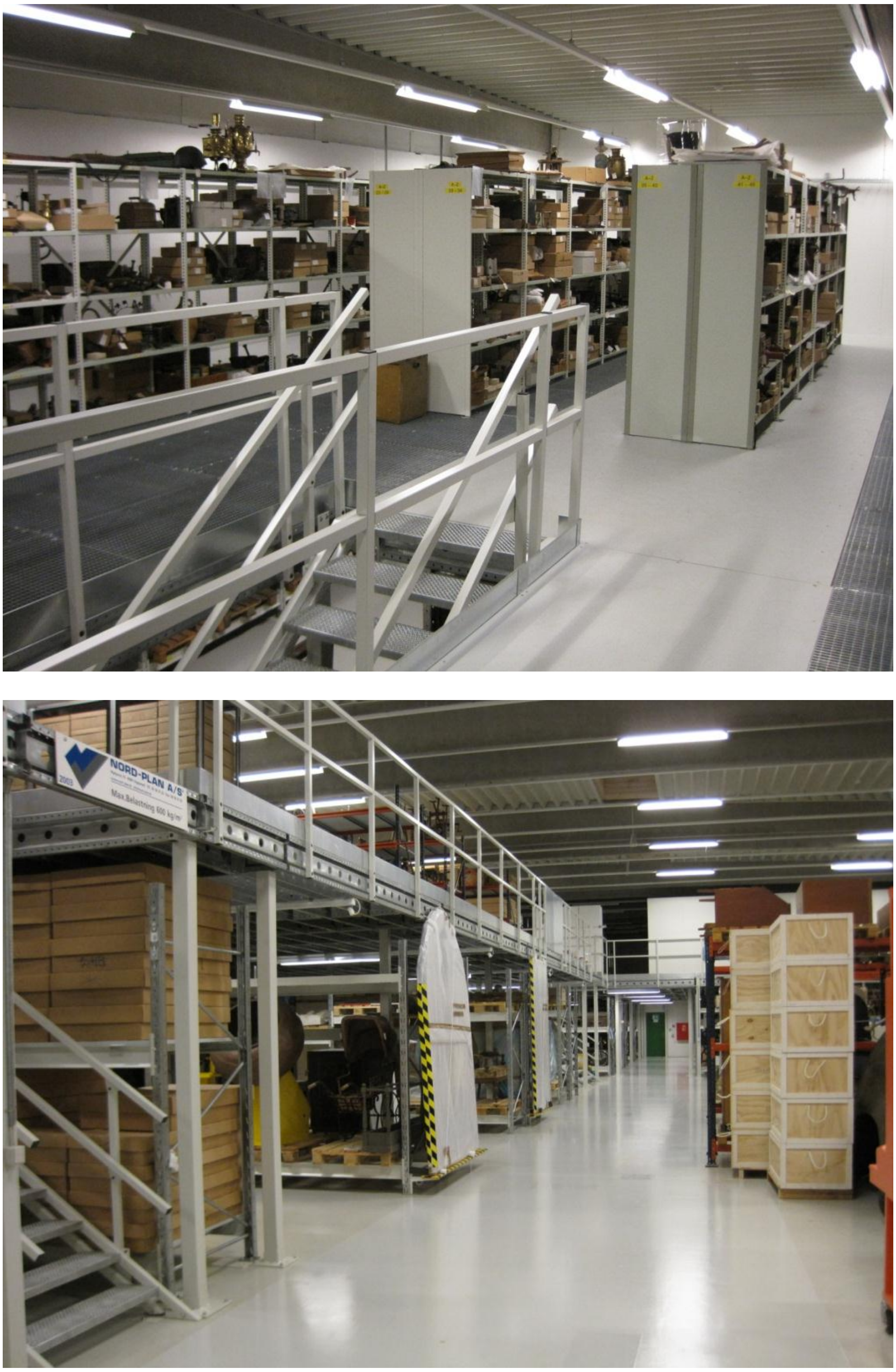


Fig. 4.14. Inside Vejle basic climate storage hall (top: mezzanine, bottom: ground floor).

Fig. 4.15. This one desiccant dehumidifier controls the entire basic climate storage area in Vejle (approximately 17,000 m^3). Model: Munters MLT 800, max. power consumption at full load 5.12 kW, nominal airflow 800 m^3/hour, approximate dehumidification capacity for maintaining 50% RH at 12 °C: 2.8 kg/hour (data from Munters product information).

5. Climate and energy, main sites: Randers storage building

Fig. 5.1. The storage facility in Randers.

5.1 General information

The storage building of 'Fællesmagasinet for museer i Midt- og Østjylland' (managed by Museum Østjylland) is located at Lollandsvej 10, DK-8940 Randers SV.

The facility consists of one large building, which houses a large storage room providing a basic storage climate (about 55% RH) and a smaller storage room providing a dry storage environment (about 30% RH). At one end of the building is located an area for receiving goods and museum objects, including an inspection room, and a large freezer for pest eradication. At the same end of the building, on the second floor, diverse staff facilities are located (office, kitchen) as well as a technical room for the ventilation and climate control systems. See floor plan in Fig. 5.2.

The large basic climate store is 1640 m^2 with 7 m height at the centre of the building (volume 11,300 m^3), and mainly equipped with compact shelves of full height. The smaller dry climate storage room is 312 m^2 with a height of 7 m (volume 2080 m^3).

The building is a purpose built museum store, constructed and taken into use in 2008. Storage rooms were empty during the first year of measurements, and from then on gradually filled.

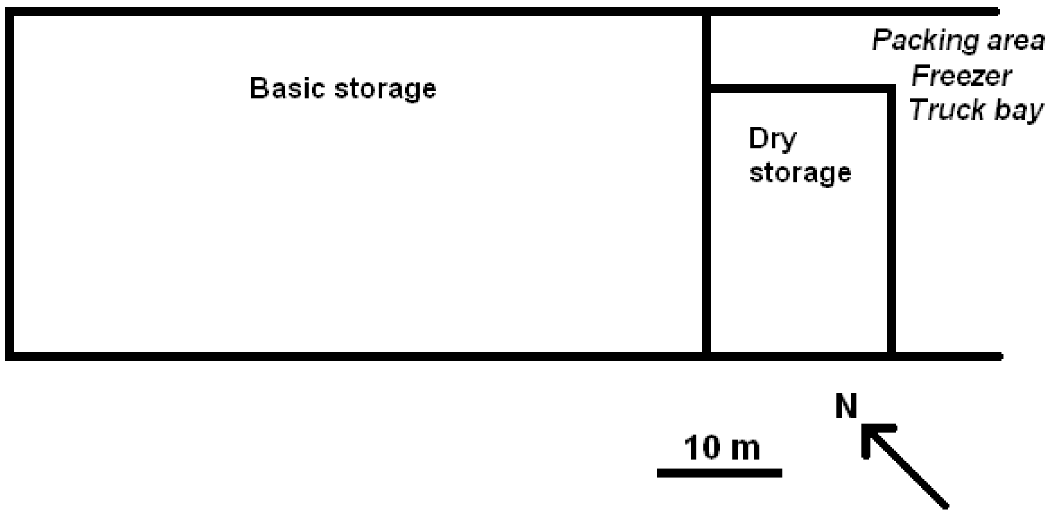


Fig. 5.2. Floor plan (approximately to scale) of storage areas.

Fig. 5.3. Aerial photo of the Randers storage building (in centre). Source: Google Earth.

5.2 Construction and insulation

The walls of the storage rooms are constructed as (from inside to outside): Pre-cast concrete elements (240mm lightweight concrete), mineral wool (250mm), 18 mm corrugated steel cladding, silver metallic finish. U-value: 0.13 W/m^2K.

The roof is (from inside to outside): Profiled metal deck between double ‘T’ girders, mineral wool (300 mm), 2 layers of bitumen roofing. The roof has a slight pitch. U-value: 0.12 W/m^2K.

The floor is (from inside out): concrete (120 mm), gravel drainage layer (150 mm), with no thermal insulation. U-value: 41 W/m^2K.

Both the basic and the dry climate storage room are located on the ground floor.

5.3 Climate control

Each storage room is equipped with a desiccant wheel dehumidifier (Munters ML17), which together with a ventilation fan draws and blows air to and from the storage rooms in a closed circuit. The re-circulation of air is constantly on, but the air speed can modulate up and down, while the dehumidifier only runs when needed (when the RH is too high inside the storage room). The large basic climate storage room has a re-circulation rate of about 0.2 room volume per hour (0.68 m^3/s) when the re-circulation is on normal (highest) flow-rate. There is no mechanical intake of outdoor air now, however, until October 2009 the stores had 10% over pressure created by the intake of ambient air.

Since November 2009 the set-point for the basic climate zone was raised from 50% to 55% RH.

There is no direct heating of the storage rooms; however, some heat will escape the climate control systems, as well as some heat will leak through the walls from the adjacent heated staff facilities (most apparent for the dry climate zone store).

5.4 Climate: Yearly statistics

Table 5.1: Basic climate storage hall. Climate control set-point: 50% RH (-2009), 55% RH (2010-). No temperature control. The climate is graphed in Figs. 5.4-5.6.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2009	13 (8-19)	50 (40-56)	89	Dehum + fan: 35355	3.13	RH set-point changed from 50% to 55% in November
2010	12 (7-19)	54 (48-63)	92	Dehum + fan: 32131	2.85	

Table 5.2: Dry climate storage room. Climate control set-point: 30% RH. No temperature control. The climate is graphed in Figs. 5.7-5.9.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2009	15 (9-21)	31 (24-39)	125	Dehum + fan: 18750	9.01	
2010	13 (7-21)	31 (25-40)	149	Dehum + fan: 15763	7.58	

Table 5.3. Temperature gradient [°C] in centre of basic climate storage room (floor to ceiling), as measured four times over one year.

Height above floor	1-2-2010 12:00	1-5-2010 12:00	1-8-2010 12:00	1-11-2010 12:00
6.4 m (0.5 m below ceiling)	7.5	10.9	18.1	13.6
3 m	7.3	10.5	17.7	13.2
1 m	7.6	10.4	17.3	13.4
Floor surface	8.0	10.2	16.9	13.8

5.5 Trends and episodes

5.5.1 Basic climate storage area

The annual temperature variation for the basic climate storage area is about 7-19 °C (Table 5.1). The lowest temperature is reached around end of February or in March, and the highest temperature occurs in late July or in August (Figs. 5.4-5.6).

Over the year the RH was maintained at a constant level by the dehumidifier. However, on a short term basis sudden RH variations of up to 5% RH occur when the dehumidifier starts up. Until November 2009 the set-point for the basic climate store was 50% RH; however it was then deliberately changed to 55% RH (Fig. 5.5).

The indoor climate results in a time-weighted preservation index (TWPI) of about 90.

The energy consumed to maintain this indoor climate was about 3 kWh/m^{3}y for 2009-2010. Except for a few weeks during winter there was an almost constant need for dehumidification all year (Fig. 5.10).

The temperature gradient from the floor surface to just below the ceiling was monitored for 18 months in the centre of the basic climate storage hall. In Table 5.3 the temperature at four different heights is listed for one day in winter, spring, summer, and fall. The highest temperature difference (ceiling – floor) was measured on 10-07-2010: **+1.7 °C** (room air warmer than floor surface).

The lowest temperature difference (ceiling – floor) was measured equally on, respectively, 19-12-2009 and 20-12-2009: **-1.3 °C** (room air colder than floor surface).

5.5.2 Dry climate storage area

The annual temperature variation for the dry climate storage area is about 8-21 °C (Table 5.2). The lowest temperature is reached in February, and the highest temperature occurs in July or August (Fig. 5.7-5.9).

The RH is maintained at a very constant level by the dehumidifier, at about 38% RH. During 2010 the RH varied slightly, from 31% RH during winter to 39% RH at the peak of summer.

In 2008 the dehumidifier was turned off for about one week during June during which time the RH rose to about 45% (Fig. 5.7).

The indoor climate results in a time-weighted preservation index (TWPI) of about index 135.

During one year the RH was maintained at a constant level by the dehumidifier. However, on a short term basis sudden RH variations of up to 5% occur when the dehumidifier starts up.

The energy consumed to maintain this indoor climate was about 8.3 kWh/m^{3}y for 2009-2010. There was an almost constant need for dehumidification during the year (Fig. 5.10).

5.6 Climate graphs

5.6.1 Basic climate storage area

Legend: Temperature (red) and relative humidity (blue)

Fig. 5.4. Randers basic climate, 2008.

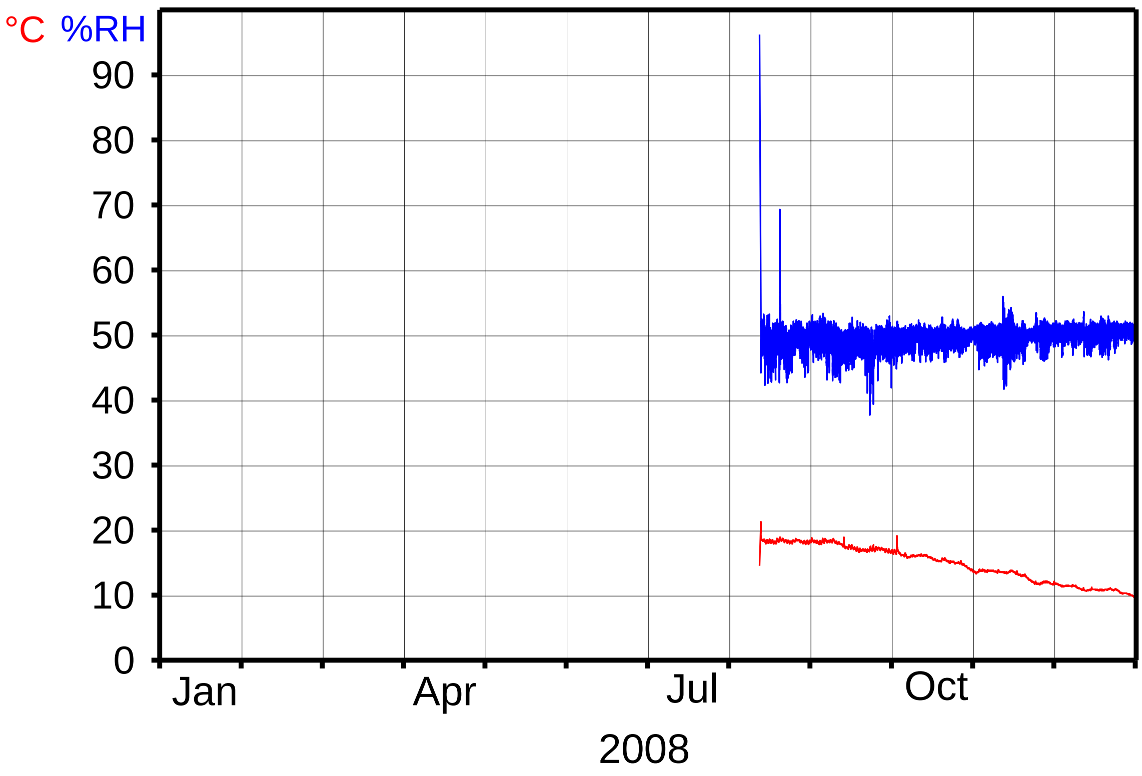


Fig. 5.5. Randers basic climate, 2009. The RH control set-pointwas raised from 50% to 55% in November. Most of January and February data is missing.

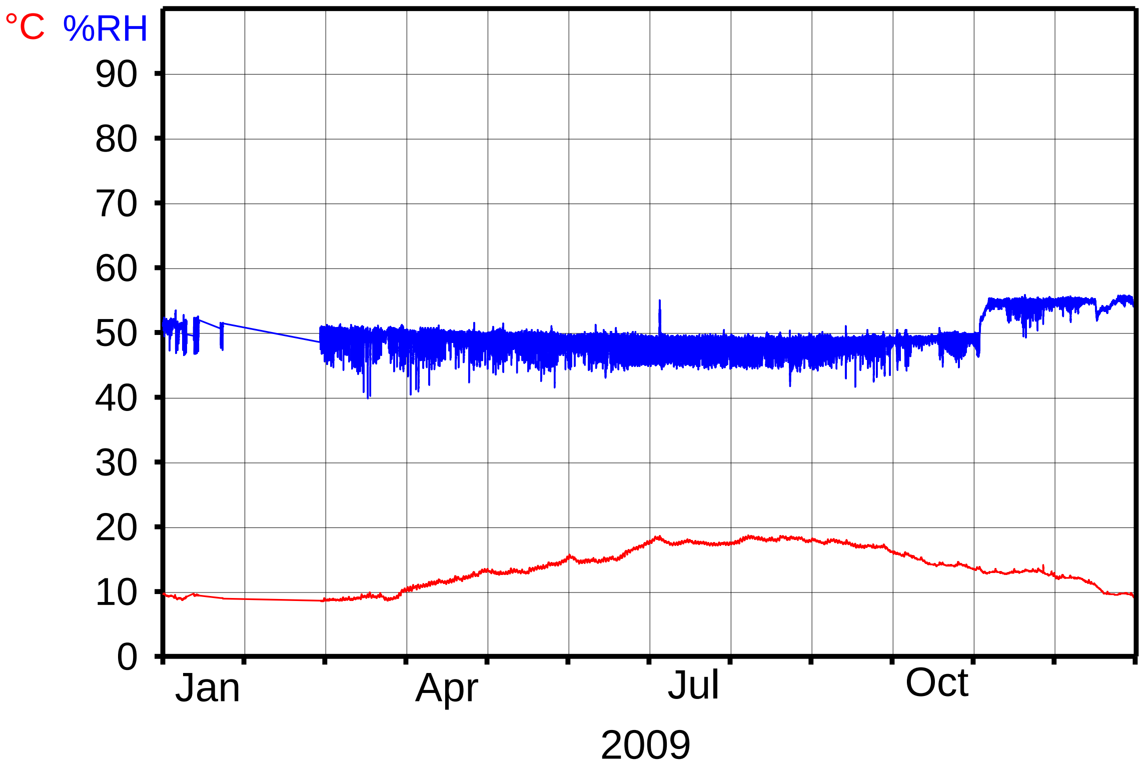
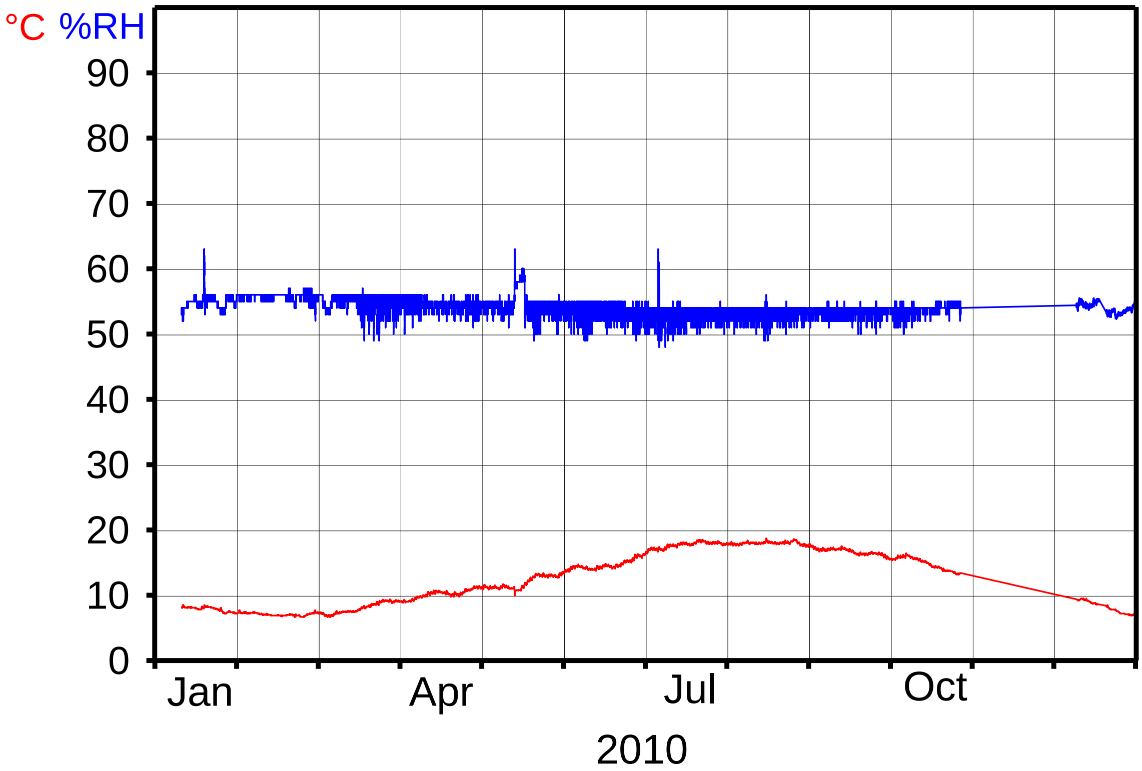


Fig. 5.6. Randers basic climate, 2010. Data for November is missing.



5.6.2 Dry climate storage area

Fig. 5.7. Randers dry climate, 2008.

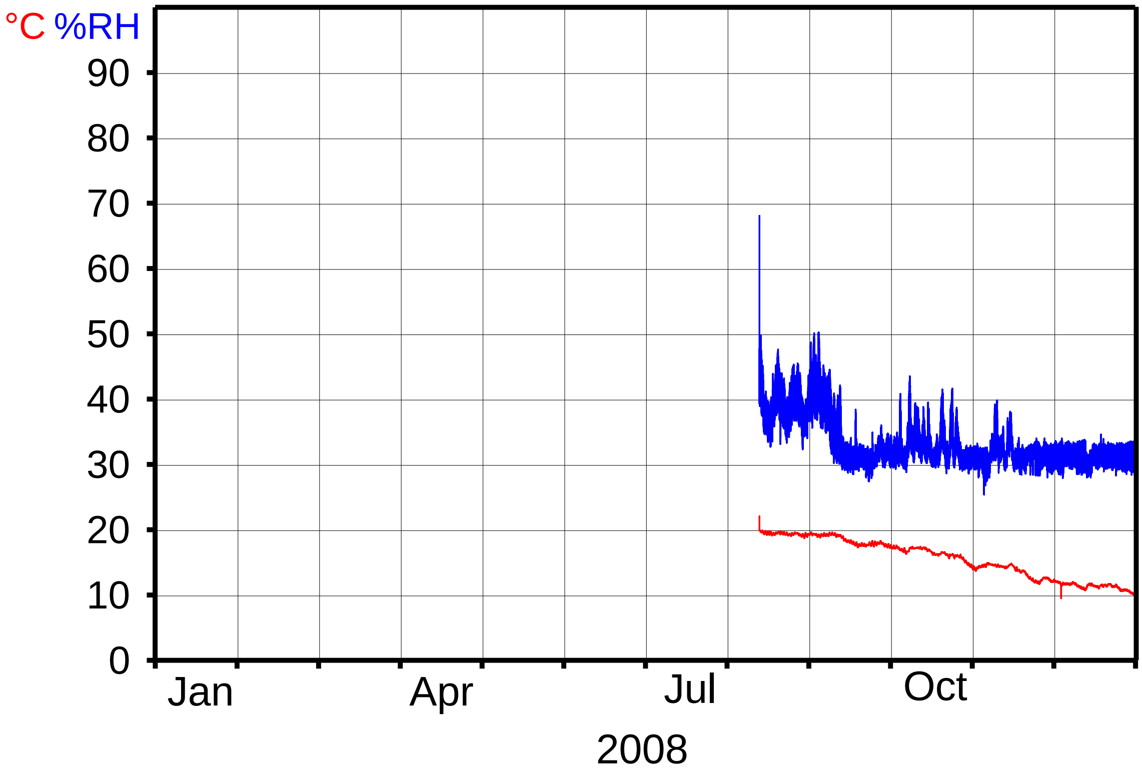


Fig. 5.8. Randers dry climate, 2009. Most of January and February data is missing.

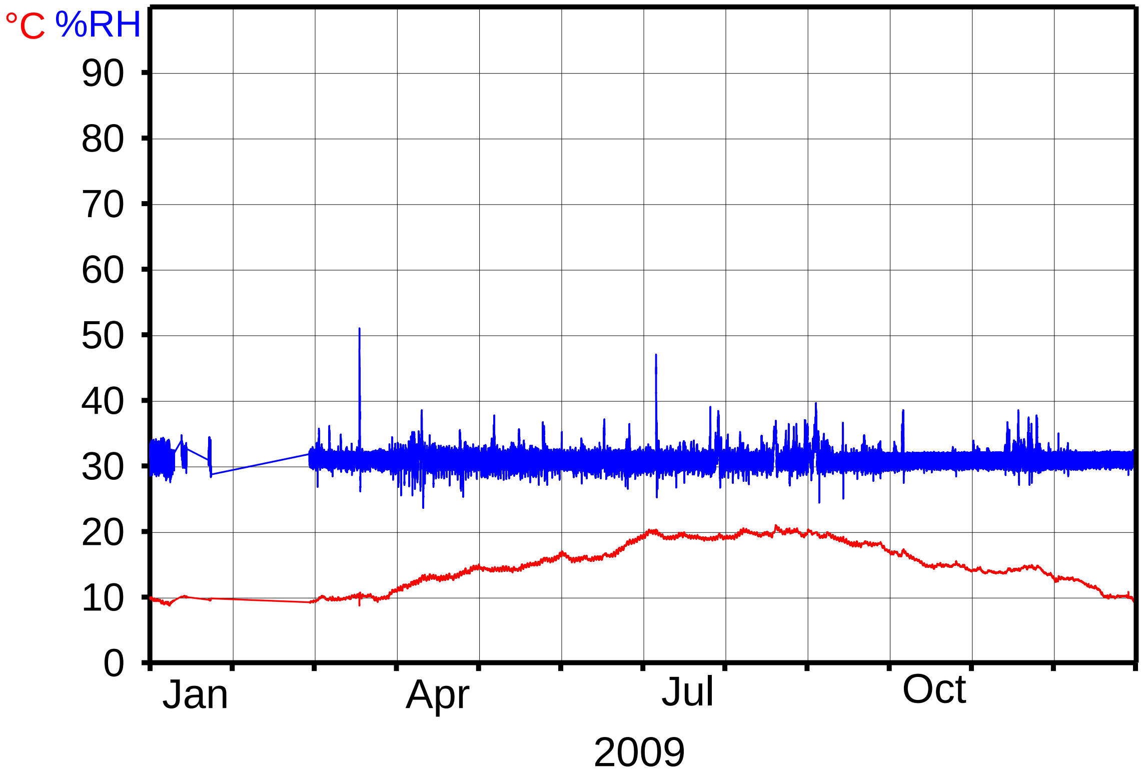
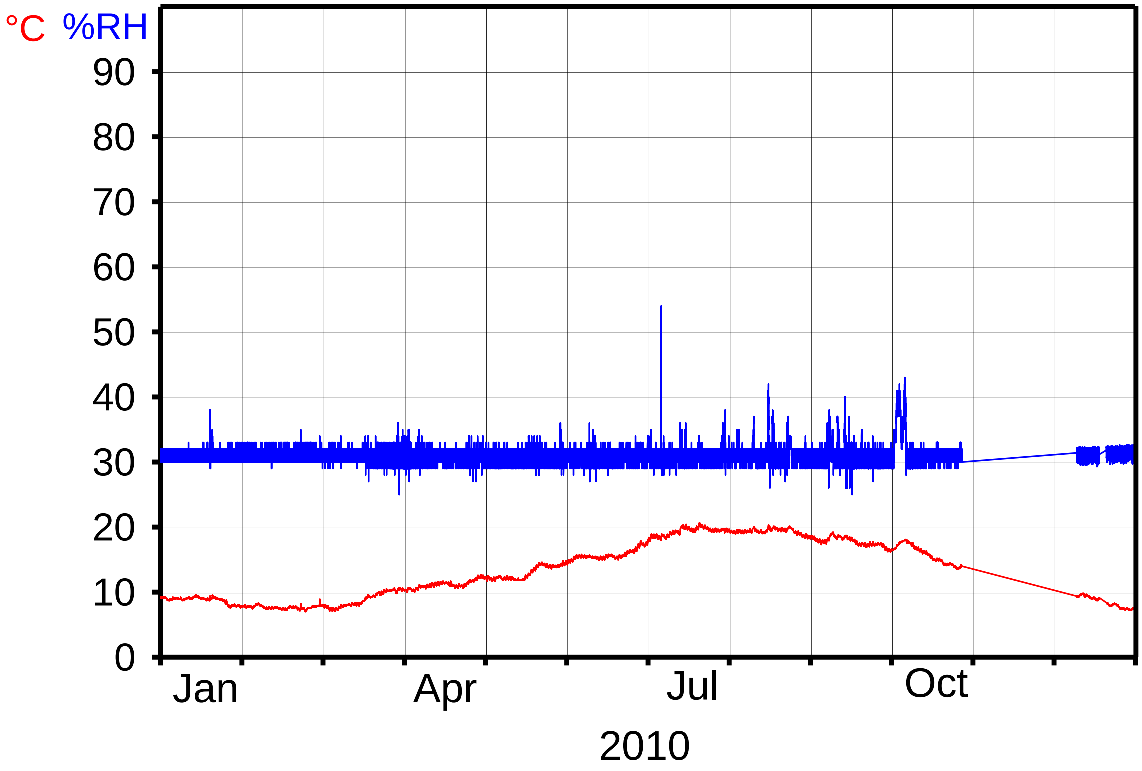


Fig. 5.9. Randers dry climate, 2010. Data for November is missing.



5.7 Energy usage graph

Fig. 5.10. Accumulated energy consumption for dehumidifier and fan in basic climate storage area (purple) and dry climate storage area (green).

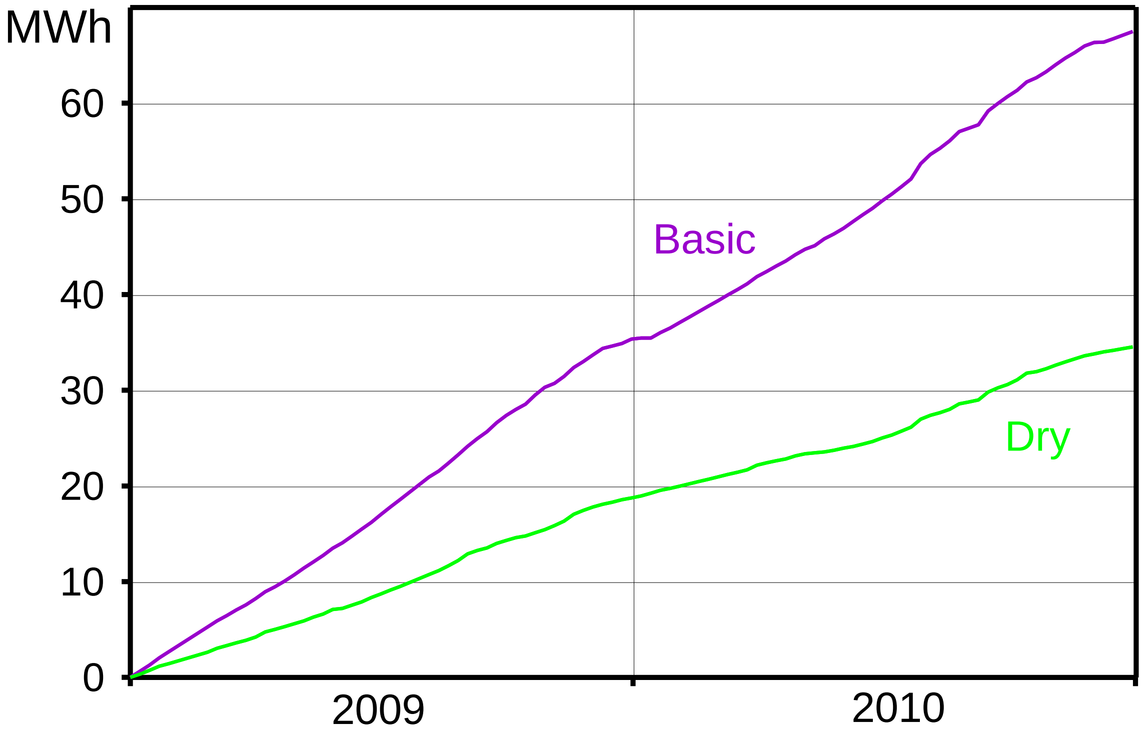


Fig. 5.11. Inside Randers basic climate storage hall

Top: compact shelves in main are. Bottom: compact shelves below mezzanine.

6. Climate and energy, main sites: Ørholm storage building

Fig. 6.1. The storage building "P" in Ørholm (National Museum of Denmark).

6.1 General information

The storage facility in Ørholm consists of several buildings, and holds approximately one-third of the National Museum's total storage area. For this project Ørholm's Hall P was investigated. The facility is located at Ørholm Stationsvej 1, DK-2800 Kgs. Lyngby.

Hall P consists of one large building, which houses three long halls of almost equal size situated side by side. The halls are connected to each other by large sliding doors (total volume 11,000 m^3). At the one end of the building a small depot for crates and boxes (not collection items) is located. This depot is heated but not humidity controlled. The technical room containing the ventilation and climate control system is also located at this end of the building. A large roll-up door opens from the middle hall to the outside. See floor plan in Fig 6.2.

The three halls have a total floor area of 1500 m^2 with varying height (maximum at roof top about 8.7 m), and are equipped with a combination of shelves on two floors (divided by a mezzanine) and open space areas for large objects.

The building is a purpose built museum store, which was constructed and taken into use in 1991. The store was full during the time of measurements.

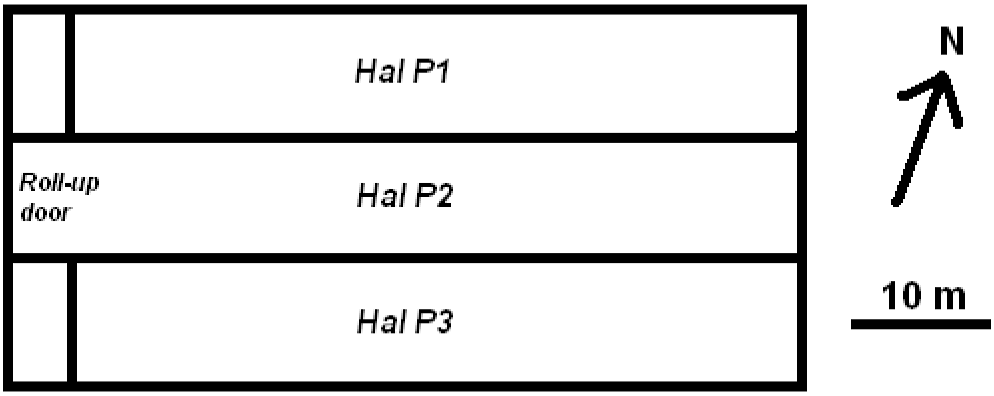


Fig. 6.2. Floor plan (approximately to scale) of storage areas inside Building P.

Fig. 6.3. Aerial photo of the Ørholm storage facility (Building P marked in red). Source: Google Maps.

6.2 Construction and insulation

The walls of the storage rooms are constructed as (from inside to outside): Steel pillows, aerated concrete elements (Sioprex) with plaster and lime wash (250 mm), air gap and painted wood facade. U-value: 0.35 W/m^{2}K.

The roof is (from inside to outside): Steel beams, Gypsum board , 150 mm mineral wool, air gap and roofing asphalt paper on wood board. U-value: 0.17 W/m^{2}K.

The floor is (from inside out): Concrete (approximately 200 mm) on compressed gravel, with no thermal insulation. U-value: 0.41 W/m^{2}K.

6.3 Climate control

The storage room is equipped a ventilation system consisting of two desiccant wheel dehumidifiers (Cortes MT1000 and DehuTech DT800), a humidifier (CondAirMatic MC 490), and a heating element. A ventilation fan draws and blows air to and from the storage rooms in a closed circuit. The re-circulation rate is 12.000 m^3/hour (about 1 room volume per hour). The system can be manoeuvred to take in fresh air from outdoors at a rate of 6000 m^3/hour, however; this setting is today not engaged due to energy saving reasons.

The halls are designed for a basic storage climate (set-point 55% RH) with a minimum-temperature set-point of 10 °C. The entire building is assumed to have a uniform climate, and air from the three halls is mixed during conditioning.

6.4 Climate: Yearly statistics

Table 6.1: Basic climate (room P2). Climate control set-point: 55% RH and >10 °C climate is graphed in Figs. 6.4-6.6.

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2008	14 (6-24)	58 (50-64)	62	Not measured	Not measured	
2009	10 (4-24)	55 (48-61)	73	Not measured	Not measured	
2010	13 (8-22)	55 (44-65)	73	Humidity control + fan: 58400 Heat: 47500	9.6	Estimated energy use for heating

Table 6.2. Temperature gradient [°C] in centre of the storage building's room P2 (floor to ceiling), as measured four times over one year.

Height above floor	1-2-2010 12:00	1-5-2010 12:00	1-8-2010 12:00	1-11-2010 12:00
8.2 m (0.5 m below ceiling)	12.5	15.4	22.5	13.8
3 m	11.5	14.8	20.5	13.4
1 m	10.9	14.5	20.2	13.4
Floor surface	10.5	13.6	19.9	13.1

6.5 Trends and episodes

6.5.1 Basic climate storage area

The annual temperature variation for the basic climate storage area is typically 10-23 °C; however, some years show short-term drops to 5 °C (Table 6.1). The lowest temperature is reached during December-January-February, where it is almost constantly about 10 °C. The highest temperature occurs in July (Figs. 6.4-6.6).

The RH is maintained at between 50% and 60% RH (peak values of 65% RH). In early 2010 the level decreased to about 45% RH for some months due to mechanical problems (Fig. 6.6).

The indoor climate results in a time-weighted preservation index (TWPI) of about index 73.

In 2010 the energy consumed to maintain this indoor climate was 5.3 kWh per m^3 of storage space, for ventilation and humidity control. The additional contribution by heating has not been quantified, but based on U-value and normal heating pattern of the building (10 °C in the period November-March) we estimate this to 4.3 kWh per m^3.

The dehumidification need is highest during summer, while the humidification need mainly lies in winter due to the slightly increased indoor temperature.

The temperature gradient from the floor surface to just below the ceiling was monitored for 18 months in the centre of the building (middle hall). In Table 6.2 the temperature at four different heights is listed for one day in winter, spring, summer, and fall. The highest temperature difference (ceiling – floor) was measured on 10-07-2010: **+6.8 °C** (room air warmer than floor surface). The lowest temperature difference (ceiling – floor) was measured equally on, respectively, 14-10-2009, 17-10-2009, and 02-12-2009: **-1.1 °C** (room air colder than floor surface).

6.6 Climate graphs

Legend: Temperature (red) and relative humidity (blue)

Fig. 6.4. Ørholm basic climate (room P2), 2008.

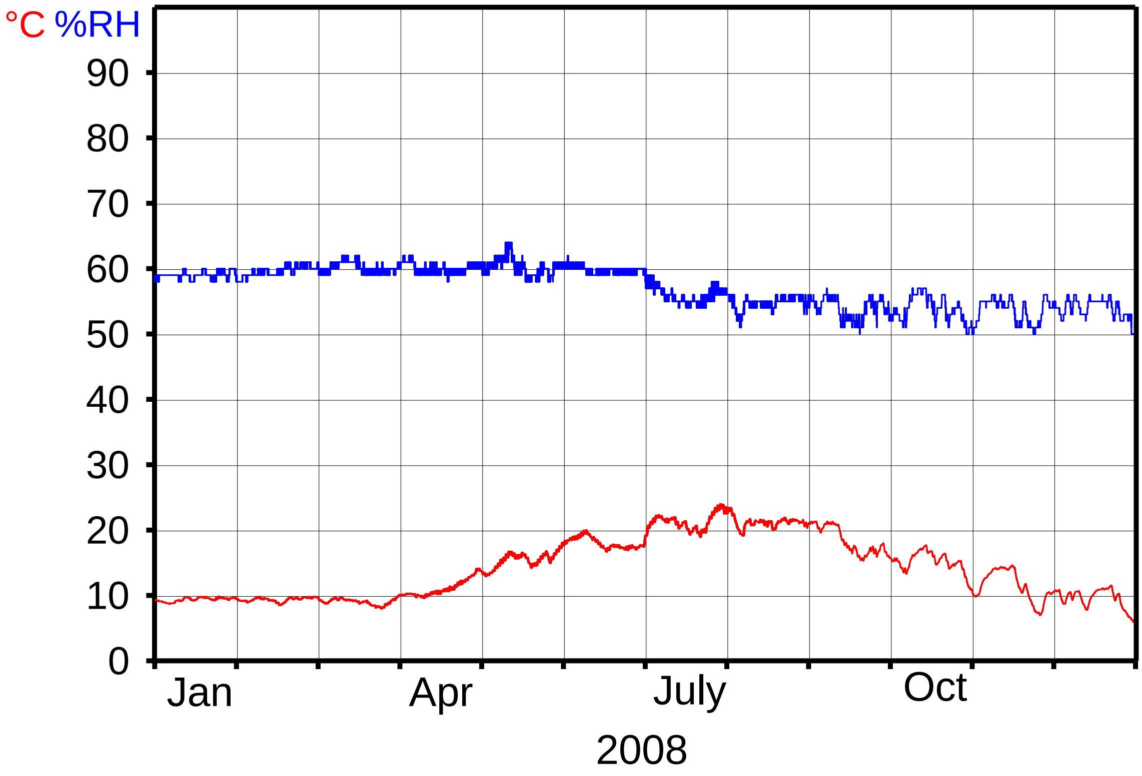


Fig. 6.5. Ørholm basic climate (room P2), 2009.

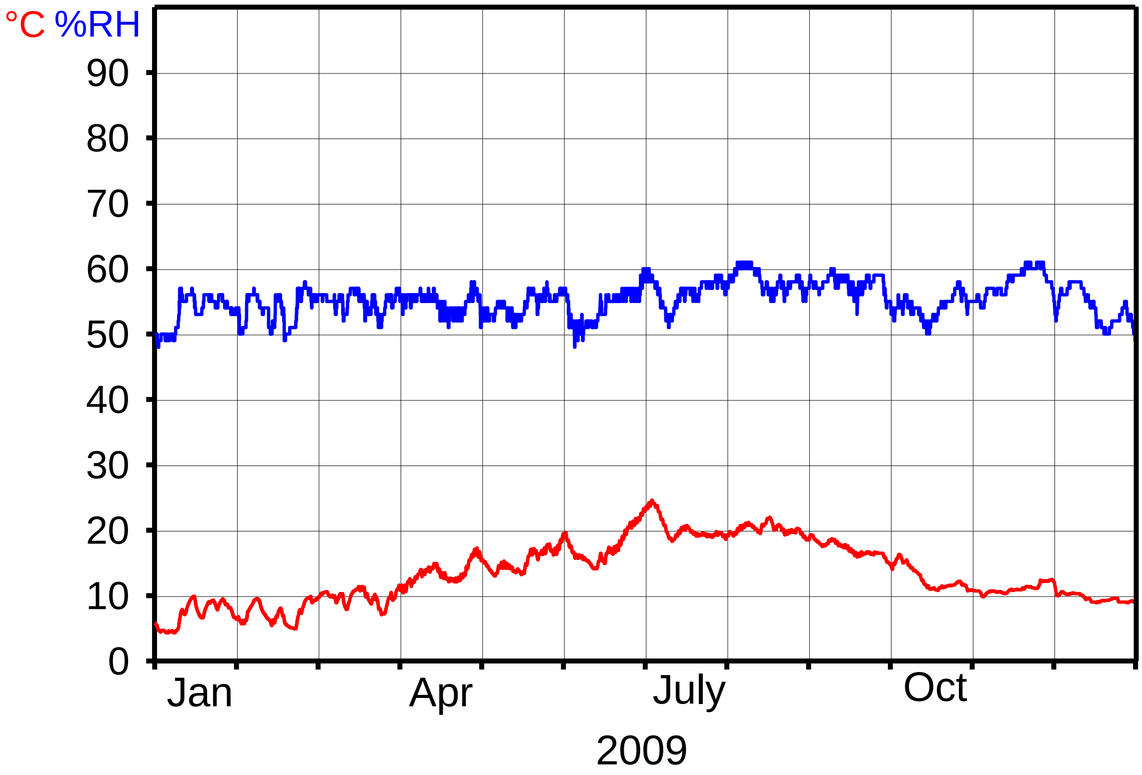


Fig. 6.6. Ørholm basic climate (room P2), 2010.

6.7 Energy usage graph

Fig. 6.7. Accumulated energy consumption for fan, dehumidifier and humidifier (excluding heating).

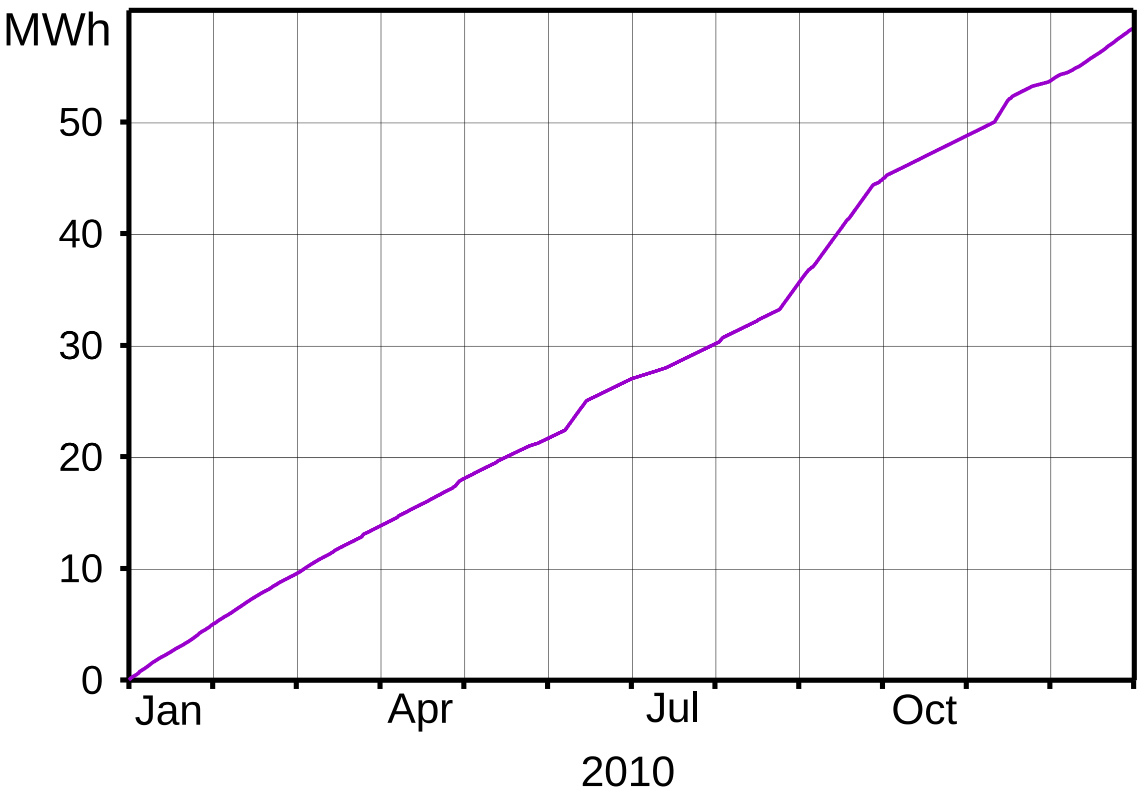


Fig. 6.8. Inside Ørholm Building P.

Top: Hall P2. Bottom: Hall P1.

7. Air quality
Main sites: Ribe, Vejle, Randers, and Ørholm

7.1 Pollutant species

All four main sites were monitored for air pollution several times during the period December 2008 – January 2010. All measurements were carried out in the basic climate storage areas.

Pollution concentrations were measured indoors and outdoors for the pollutants nitrogen dioxide (NO_2), ozone (O_3), ammonia (NH_3), and hydrogen sulphide (H_2S). Organic acids (acetic and formic) were measured indoors only.

These pollutants are known to cause material deterioration; ozone by direct oxidation, and the others (mainly) by engaging in acid hydrolysis. Damage types include metal corrosion, dye fading, discolouration of organic materials (e.g. paper), and polymer breakdown in organic materials such as paper, textiles, plastic, and rubber.

Nitrogen dioxide originates from combustion processes (e.g. heating and traffic). The ambient NO_2 level is highest in winter. Ozone is a natural pollutant which is formed from photo-chemical reactions in the atmosphere, which are driven by sun light. In Denmark the ambient ozone level is therefore highest in summer.

Ammonia may have both outdoor and indoor sources, however, of different origin. Outdoor ammonia is mainly a farming pollutant from manure, which is spread on fields as a fertilizer in the spring months March and April. Other outdoor sources include atmospheric reactions among combustion products, e.g. nitrogen compounds from traffic. Indoor sources include certain cleaning agents.

Acetic and formic acid are primarily indoor-generated pollutants, which are emitted from materials in the building's interior or furniture (or museum objects). The primary source is wood based products; however, some "wet" products such as paints and fillers may emit organic acids when curing.

Hydrogen sulphide has both outdoor and indoor sources. It is released from the decomposition of organic matter, and may for example be emitted from sewers.

7.2 Presentation of results

In the Tables 7.1-7.4, the measured pollution concentrations (average of several measurements) are given for each site. For ambient pollutants, the indoor-outdoor concentration ratio (I/O) is calculated as this is a measure of how well the building retards infiltration. It may be assumed that this ratio is maintained throughout the year, despite variations in the outdoor concentration, if the building's ventilation is kept at a constant rate.

The concentrations of indoor-generated pollutants (organic acids) are listed in a separate table for each site (Table 7.5-7.9). The concentration of these compounds reflects the source strength of the indoor pollution emission in relation to the air exchange rate. For each measurement campaign, the indoor average temperature is also given because temperature influences the emission rate from materials (the higher the temperature, the higher the emission rate).

7.3 Air exchange rate

The air exchange rate (the rate of exchange of indoor air with ambient air) was determined for each climate zone in a building (typically, for the large basic climate room and for the smaller dry climate room) and for the entire storage area. The air exchange rate was measured twice at all locations (once in the spring and once in the autumn of 2010). The total air exchange rate for each building is given in Table 7.10.

Besides its influence on air pollution levels, the air exchange rate has a strong influence on the humidity load indoors since infiltrating air from outside will transport excess moisture to the storage area (or, sometimes, overly dry air).

7.4 Results: ambient pollutants

Table 7.1. Nitrogen dioxide (NO_2), average concentration, all sites.

Average of eight sampling periods (December 2009 through September 2010)	Indoor concentration [ppb] (± 1 STD)	**Indoor/Outdoor concentration ratio** (± 1 STD)
Ribe basic climate store	3.1 (± 1.1)	**0.27** (± 0.09)
Randers basic climate store	3.0 (± 1.2)	**0.27** (± 0.11)
Vejle Hall A (basic climate)	3.1 (± 1.1)	**0.24** (± 0.09)
Vejle Hal C (basic climate)	3.2 (± 1.1)	**0.24** (± 0.08)
Ørholm P (room P2)	4.5 (± 0.87)	**0.35** (± 0.16)

Table 7.2. Ozone (O_3), average concentration, all sites.

Average of three sampling periods (Dec/January, June, and August 2010)	Indoor concentration [ppb] (± 1 STD)	**Indoor/Outdoor concentration ratio** (± 1 STD)
Ribe basic climate store	0.93 (± 0.45)	**0.03** (± 0.01)
Randers basic climate store	0.64 (± 0.20)	**0.02** (± 0.00)
Vejle Hall A (basic climate)	0.75 (± 0.22)	**0.02** (± 0.01)
Vejle Hal C (basic climate)	1.3 (± 1.3)	**0.04** (± 0.04)
Ørholm P (room P2)	2.4 (± 2.3)	**0.06** (± 0.05)

Table 7.3. Ammonia (NH_3), average concentration, all sites.

One sampling period (March-April 2010)	Indoor concentration [ppb] (± 1 STD)	**Indoor/Outdoor concentration ratio** (± 1 STD)
Ribe basic climate store	6.3 (± 0.17)	**0.81** (± 0.49)
Randers basic climate store	9.9 (± 2.1)	**0.30** (± 0.08)
Vejle Hall A (basic climate)	11 (± 0.06)	**1.5** (± 0.10)
Vejle Hal C (basic climate)	11 (± 0.29)	**1. 5** (± 0.10)
Ørholm P (room P2)	3.9 (± 0.88)	**1.1** (± 0.27)

Table 7.4. Hydrogen sulphide (H_2S), average concentration, all sites.

One sampling period (August 2010)	Concentration [ppb]
All sites, indoor and outdoor	All samples (indoor and outdoor) below limit of detection (<0.08 ppb)

7.5 Results: indoor-generated pollutants

Table 7.5. Organic acids, average concentration, RIBE (basic climate).

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
June 2009	0.50 (± 0.00)	0.66 (± 0.04)	1.2 (± 0.04)	14
August 2009	0.60 (± 0.02)	1.1 (± 0.17)	1.6 (± 0.15)	15

Table 7.6. Organic acids, average concentration, RANDERS (basic climate).

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
June 2009	1.1 (± 0.00)	4.1 (± 0.09)	5.2 (± 0.09)	15
August 2009	0.70 (± 0.00)	2.0 (± 0.19)	2.6 (± 0.19)	17

Table 7.7. Organic acids, average concentration, VEJLE, Room A (basic climate).

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
June 2009	0.64 (± 0.34)	1.3 (± 0.18)	2.0 (± 0.52)	14
August 2009	3.5 (± 0.42)	2.0 (± 0.22)	5.5 (± 0.64)	16

Table 7.8. Organic acids, average concentration, VEJLE, Room C (basic climate)

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
June 2009	0.64 (± 0.33)	1.2 (± 0.24)	1.8 (± 0.58)	14
August 2009	2.3 (±1.8)	2.0 (± 0.33)	4.3 (± 2.1)	16
October 2009	0.50 (± 0.00)	0.70 (± 0.28)	1.2 (± 0.28)	12

Table 7.9. Organic acids, average concentration, ØRHOLM, Room P2 (basic climate)

Ørholm P (room P2) Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
May 2009	33 (± 1.4)	14 (± 0.22)	47 (± 1.6)	19
August 2009	78 (± 5.7)	28 (± 0.62)	105 (± 6.3)	21
December 2009	12 (± 1.8)	7.3 (± 0.21)	19 (± 2.1)	11

7.6 Results: air exchange rate

Table 7.10. Overall air exchange rate for each building measured for approximately one month by the PFT-method, except (*) which was for the basic climate storage room only and measured by the 'simple concentration decay method' (using CO_2 as tracer gas) over three days.

Site	**Time**	**Air exchange rate (hour^{-1})**	**Time for one air exchange (hours)**
Ribe	*June 2009 (*)*	*0.03*	*32*
	April 2010	0.03	40
	November 2010	0.03	39
Vejle	April 2010	0.04	26
	November 2010	0.05	20
Randers	April 2010	0.03	31
	November 2010	0.04	26
Ørholm	March 2010	0.07	15
	November 2010	0.06	18

7.7 Trends

7.7.1 New buildings

The three new buildings (Ribe, Randers, Vejle) performed equally well with regard to retarding the infiltration of ambient pollutants. Ozone was reduced indoors to 2-3 % of ambient levels. Nitrogen dioxide was reduced to 24-27 % of ambient. Indoor-generated organic acids were only present at low levels (few ppb). It can be assumed that this rate of reduction between the ambient and indoors is more or less constant throughout the year, unless the ventilation regime is changed.

The low level of organic acids in the three newer buildings is very likely due to a high level of source control (the interior and furniture is made from non-emissive materials). However, especially for Ribe the fact that the storage was not yet filled with potentially-emissive objects at the time of the measurements may have played a role. The high loading of stored wooden objects is the main difference between Ørholm and the other main sites.

7.7.2 Ørholm

In Ørholm the infiltration of ambient pollutants appeared to be slightly higher; however, the difference was not significant. The indoor level of organic acids was, however, significantly higher in Ørholm than for the other buildings (up to 105 ppb). This implies that a higher level of emissions takes place, which corresponds well with the large number of wooden objects stored in the building.

Furthermore, the indoor temperature in summer is higher for Ørholm than for the other three sites, which can promote the emission of volatile organic acids.

7.7.3 Ammonia and hydrogen sulphide

Ammonia was measured once, in the spring, which in Denmark typically is the time of the year with the highest outdoor level. There seems, however, not to be any well-defined trend; at most of the sites, the indoor and outdoor levels were not very different, except for Randers where the outdoor level is three times higher than the indoor (and about four times higher than the outdoor level at other sites). This may be due to a local event, e.g., the spreading of manure on a nearby field.

Hydrogen sulphide could not be detected at any site (detection level < 0.08 ppb).

7.7.4 Air exchange

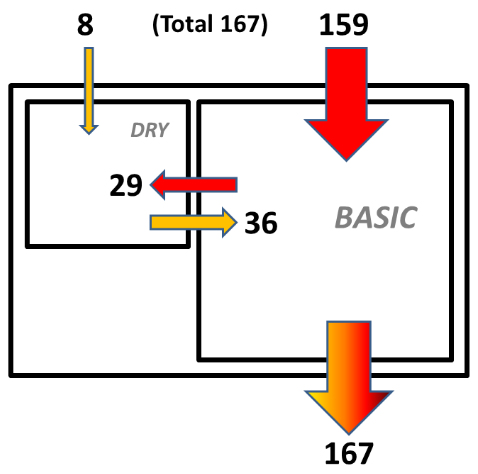
For all of the sites, the rate of exchange with ambient air was measured twice using the PFT method. The rate was typically on the order of one per day to one per one-and-a-half days (Table 7.10). The most conspicuous difference was between Ørholm and the three newer buildings, as Ørholm had an air exchange rate of about twice that of the newer buildings. However, even for Ørholm the air exchange rate was rather low compared with other types of museum buildings, e.g., exhibition galleries.

Through the use of two different tracer gases, the interchange of air between two indoor zones (two storage rooms) could be quantified (see Method, chapter 11). The interchange of air between the different storage rooms / climate zones is visualized in the Figures 7.1-7.4 .

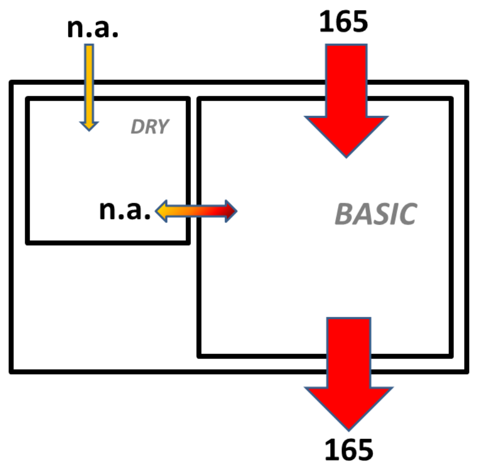
In general, for the sites with two climate zones the interchange of air between the different rooms had little influence on the large basic climate storage areas, but was a significant or the major contributor to the total air exchange of the smaller dry zones.

Fig. 7.1. Ribe storage building: interchange of air (m^3 per hour).

Total volume 6,501 m^3 (6,214 m^3 basic + 287 m^3 dry zone)



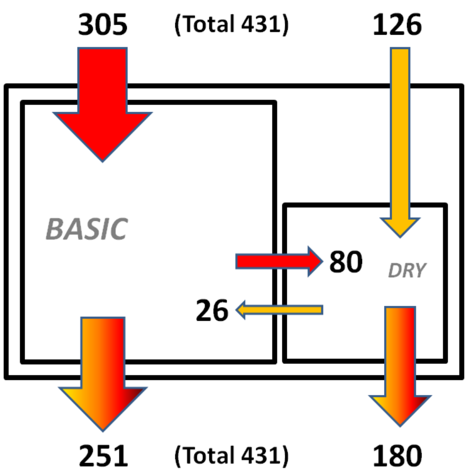
<u>April 2010 (above)</u>
The air exchange rate of the basic zone (0.03 h^{-1}) is equal to that of the entire building (0.03 $hour^{-1}$). The interchange between the basic zone and other indoor areas is low. For the dry zone, the air exchange with other indoor zones (0.10 $hour^{-1}$) is higher than the exchange between dry zone and ambient (0.03 $hour^{-1}$).



<u>November 2010 (above)</u>
Due to a defective tracer gas source the two-zone mapping could not be performed in November 2010. The air exchange rate of the basic zone (0.03 $hour^{-1}$) is assumed to be close to that of the entire building.

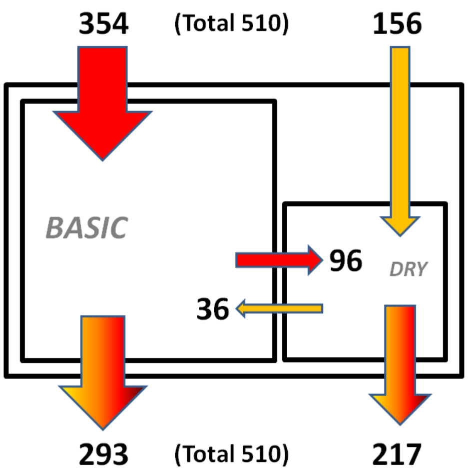
Fig. 7.2. Randers storage building: interchange of air (m^3 per hour).

Total volume 13,364 m^3 (11,284 m^3 basic + 2,080 m^3 dry zone)



<u>April 2010 (above)</u>

The air exchange rate of the basic zone (0.02 h^{-1}) is similar to that of the entire building (0.03 $hour^{-1}$). The interchange between the basic zone and other indoor areas is low. For the dry zone the air exchange with other indoor zones is significant (0.04 $hour^{-1}$) compared to the exchange between dry zone and ambient (0.06 $hour^{-1}$).

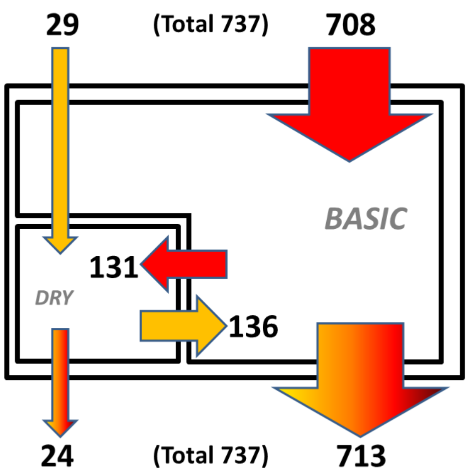


<u>November 2010 (above)</u>

The air exchange rate of the basic zone (0.03 $hour^{-1}$) is similar to that of the entire building (0.04 $hour^{-1}$). The interchange between the basic zone and other indoor areas is low. For the dry zone the air exchange with other indoor zones is significant (0.05 $hour^{-1}$) compared to the exchange between dry zone and ambient (0.08 $hour^{-1}$).

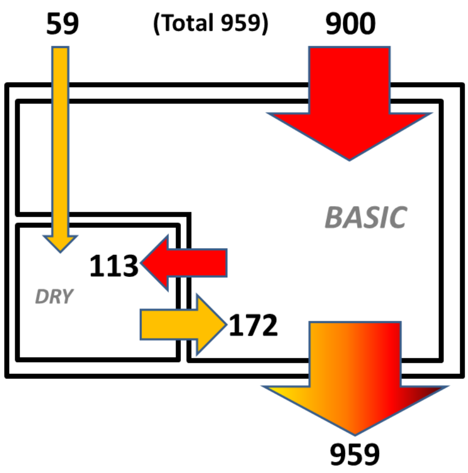
Fig. 7.3. Vejle storage building: interchange of air (m^3 per hour).

Total volume 19,438 m^3 (17,057 m^3 basic + 2,381 m^3 dry zone)



April 2010 (above)

The air exchange rate of the basic zone (0.04 hour^{-1}) is equal to that of the entire building (0.04 hour^{-1}). The interchange between the basic zone and other indoor areas is low. For the dry zone the air exchange with other indoor zones is higher (0.06 hour^{-1}) compared to the exchange between dry zone and ambient (0.01 hour^{-1}).

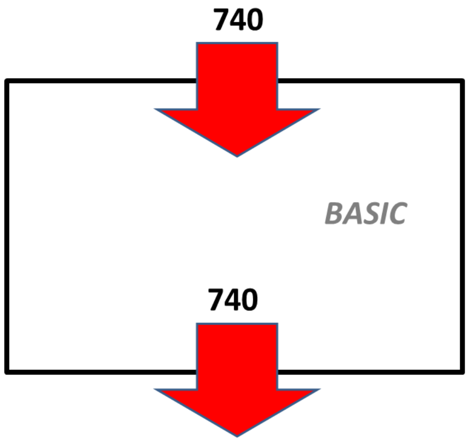


November 2010 (above)

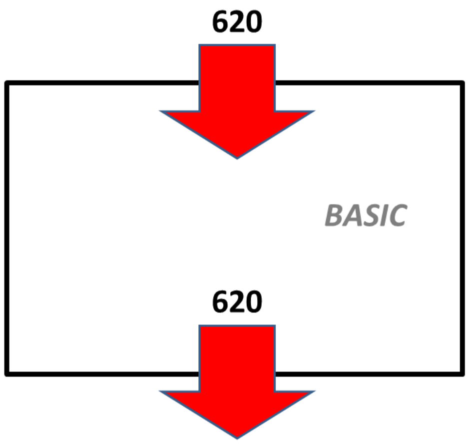
The air exchange rate of the basic zone (0.05 hour^{-1}) is equal to that of the entire building (0.05 hour^{-1}). The interchange between the basic zone and other indoor areas is low. For the dry zone the air exchange with other indoor zones is higher (0.05 hour^{-1}) compared to the exchange between dry zone and ambient (0.02 hour^{-1}).

Fig. 7.4. Ørholm storage building P: air exchange (m^3 per hour).

Total volume 11,000 m^3



<u>*March 2010 (above)*</u>
There is only one climate zone. The air exchange rate is 0.07 $hour^{-1}$.



<u>*November 2010 (above)*</u>
There is only one climate zone. The air exchange rate is 0.06 $hour^{-1}$.

8. Measurements in construction and installations: Ground and air temperature profiles, and the properties of ventilation process air

8.1 Ground temperature profile

The temperature profile of the ground below the floor inside the storage building was measured in Ribe, Ørholm, and Vejle. Ground temperature measurements were only conducted in the basic climate storage areas, but at two locations: inside the storage room approximately at the centre of the building, and at the building's edge approximately 1 m from the outer wall. In addition, outdoor measurements were conducted well away from the building (undisturbed ground). At all places monitoring was performed at 0.1 m, 0.5 m, 1 and 2 m below surface.

Measurements for one year (September 2009 – September 2010) are graphed in the following figures:

- Ribe: Figs. 8.1-8.3
- Ørholm: Figs. 8.4-8.6
- Vejle: Figs. 8.7-8.10

8.2 Air temperature profile

The above ground air temperature distribution was also monitored inside the basic climate stores, at four heights between floor surface and 0.5 m below the ceiling. The statistics from these measurements were summarized previously in Tables 3.3 (Ribe), Table 4.3 (Vejle), Table 5.3 (Randers), and Table 6.2 (Ørholm). In Randers, measurements were only conducted in the air, not in the ground.

One example of the air temperature distribution (for Vejle) is shown in Fig. 8.10, for the one year period September 2009 – September 2010 (same time period as for the ground measurements).

Fig. 8.1. Ribe ground temperature profile, at the centre of the building. Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

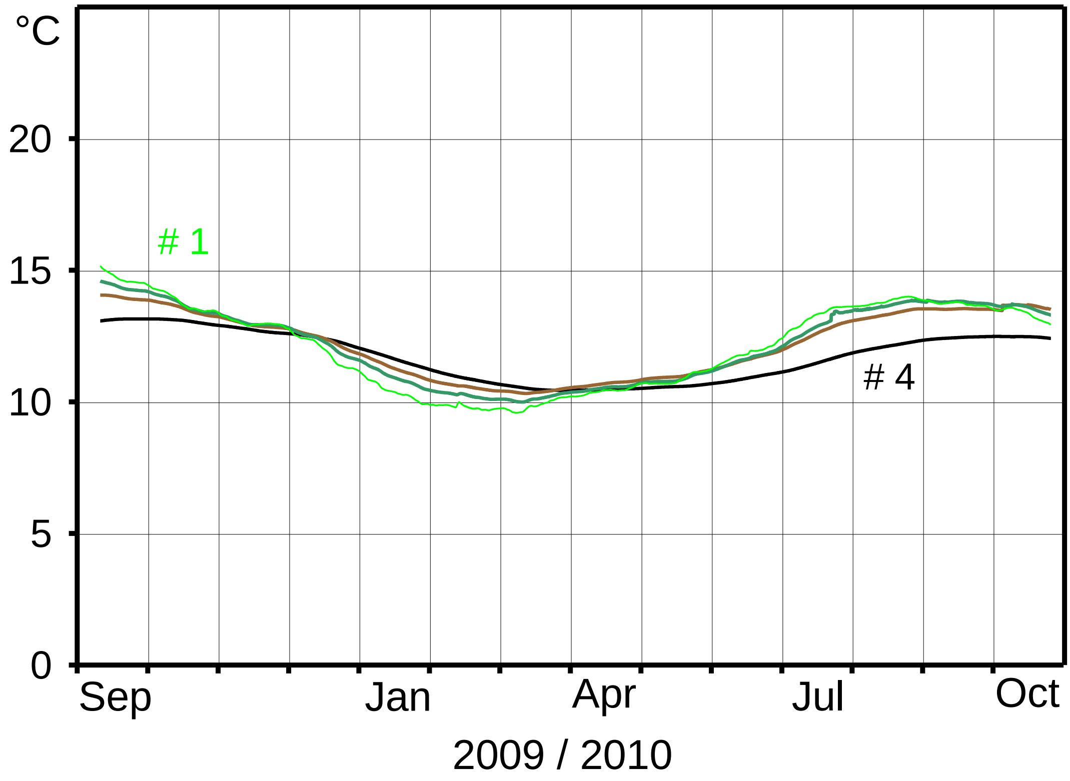


Fig. 8.2. Ribe ground temperature profile, at the edge of the building. Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

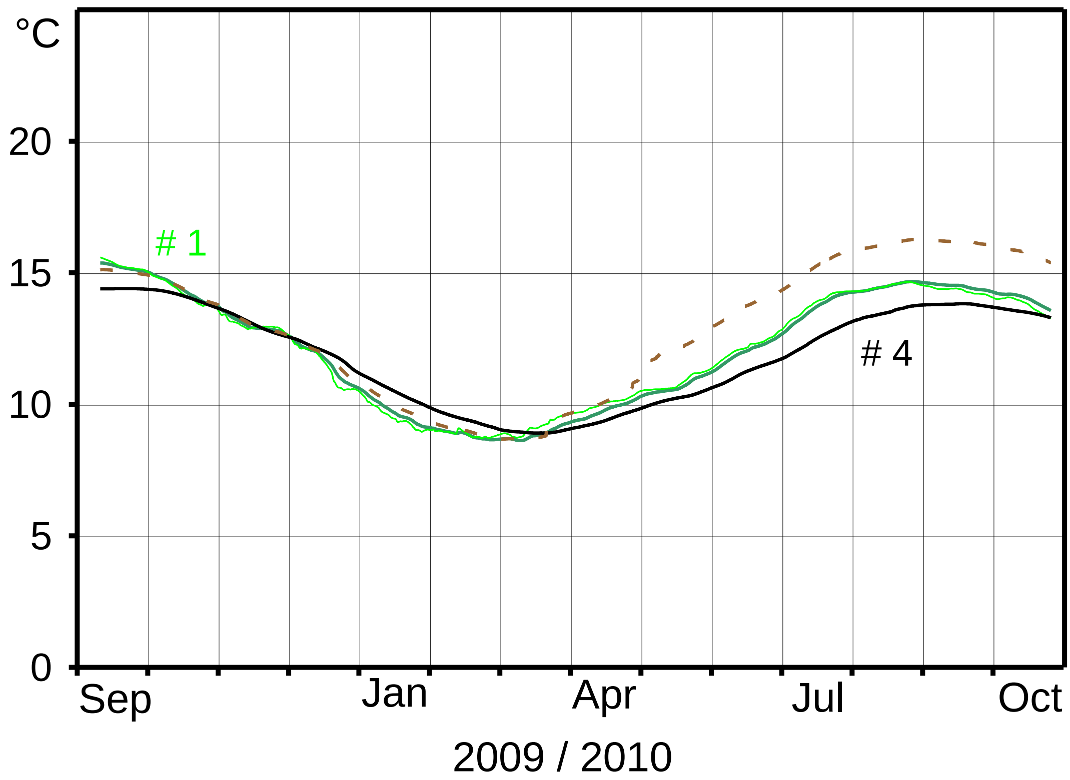


Fig. 8.3. Ribe ground temperature profile, outdoors. Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

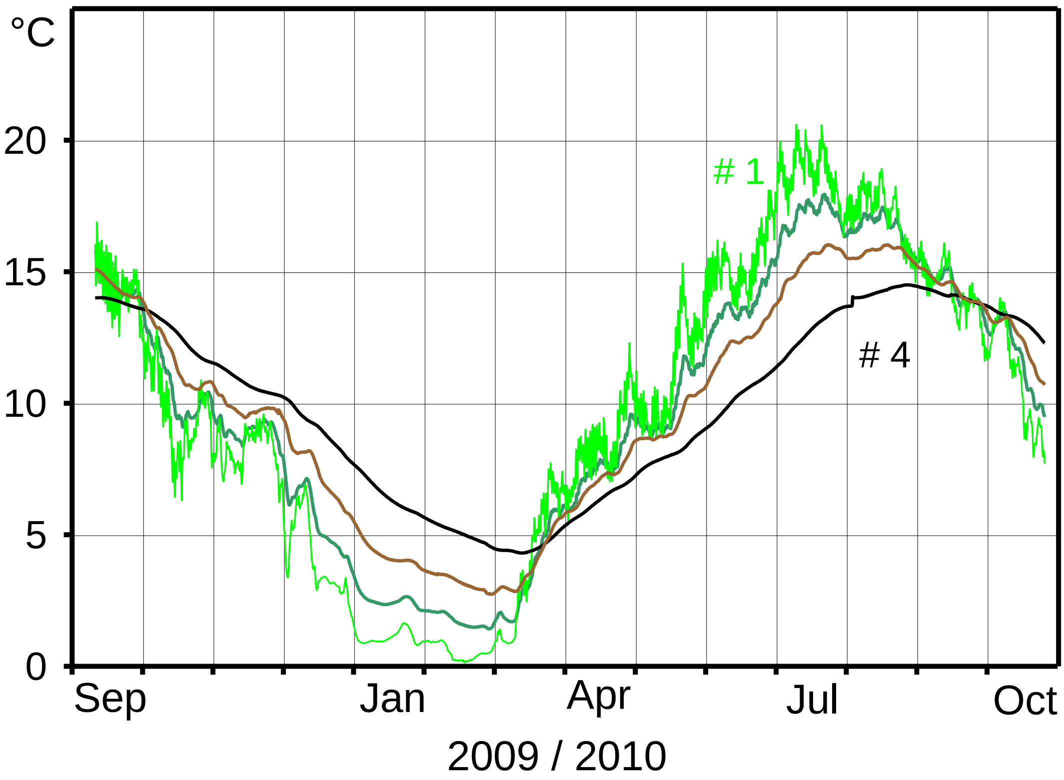


Fig. 8.4. Ørholm ground temperature profile, at the centre of the building (Hall P2). Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

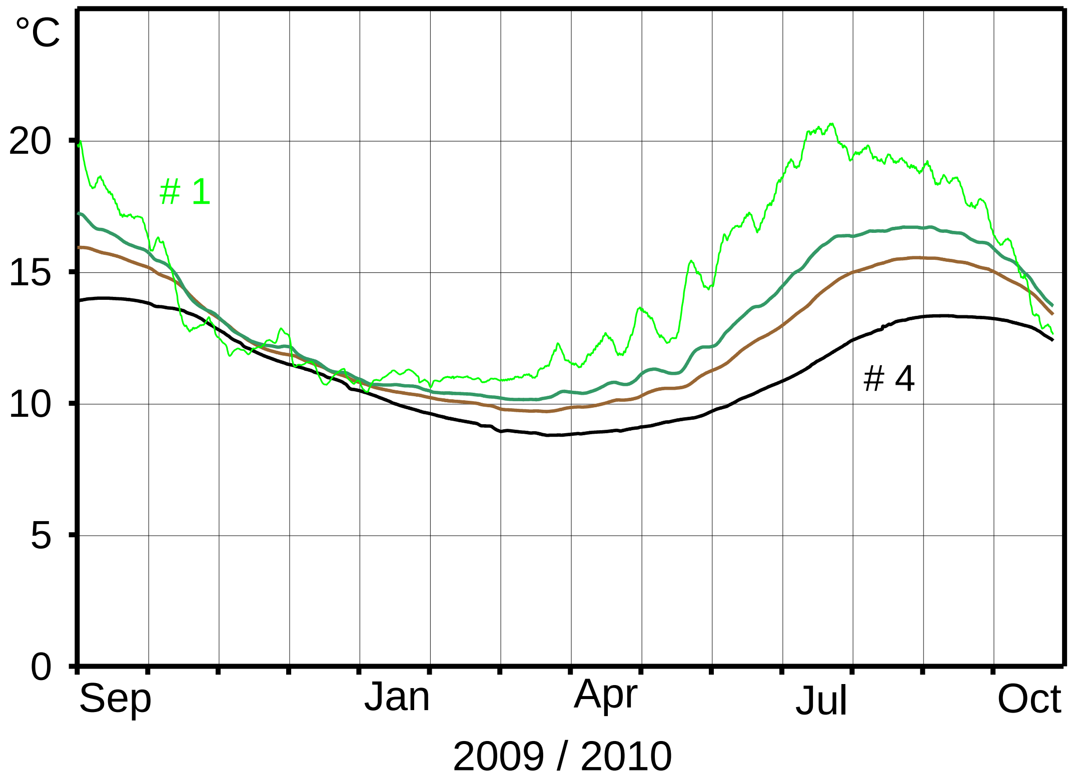


Fig. 8.5. Ørholm ground temperature profile, at the edge of the building (Hall P3). Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

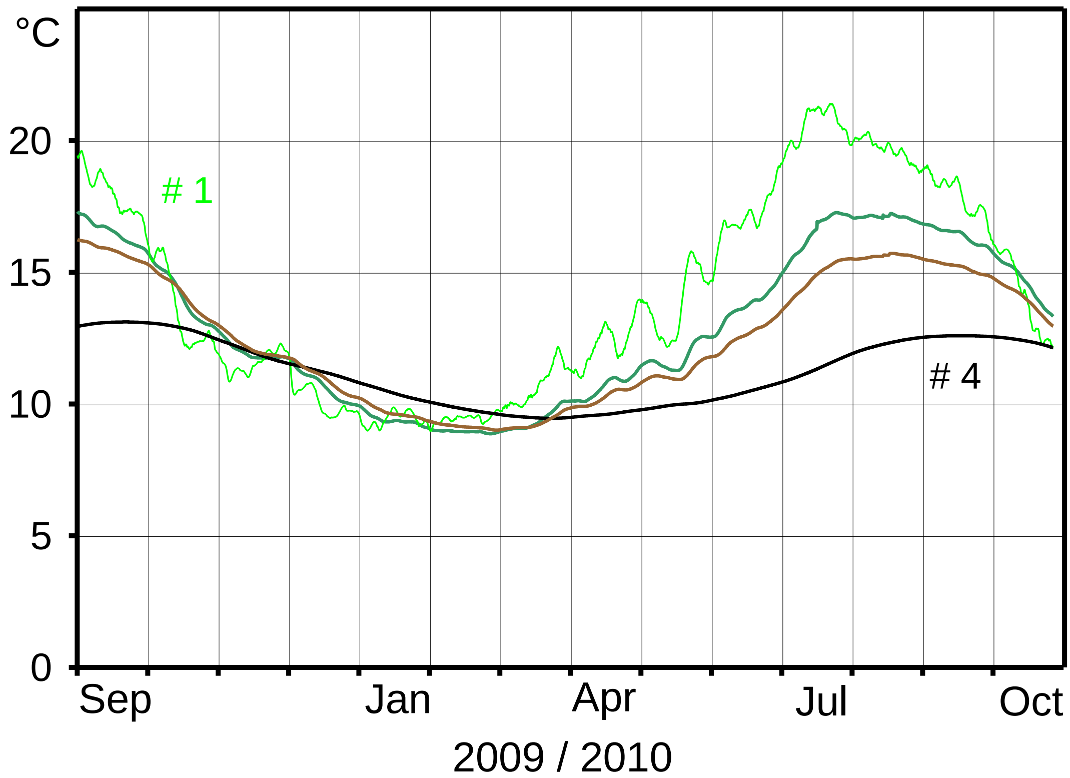


Fig. 8.6. Ørholm ground temperature profile, outdoors. Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

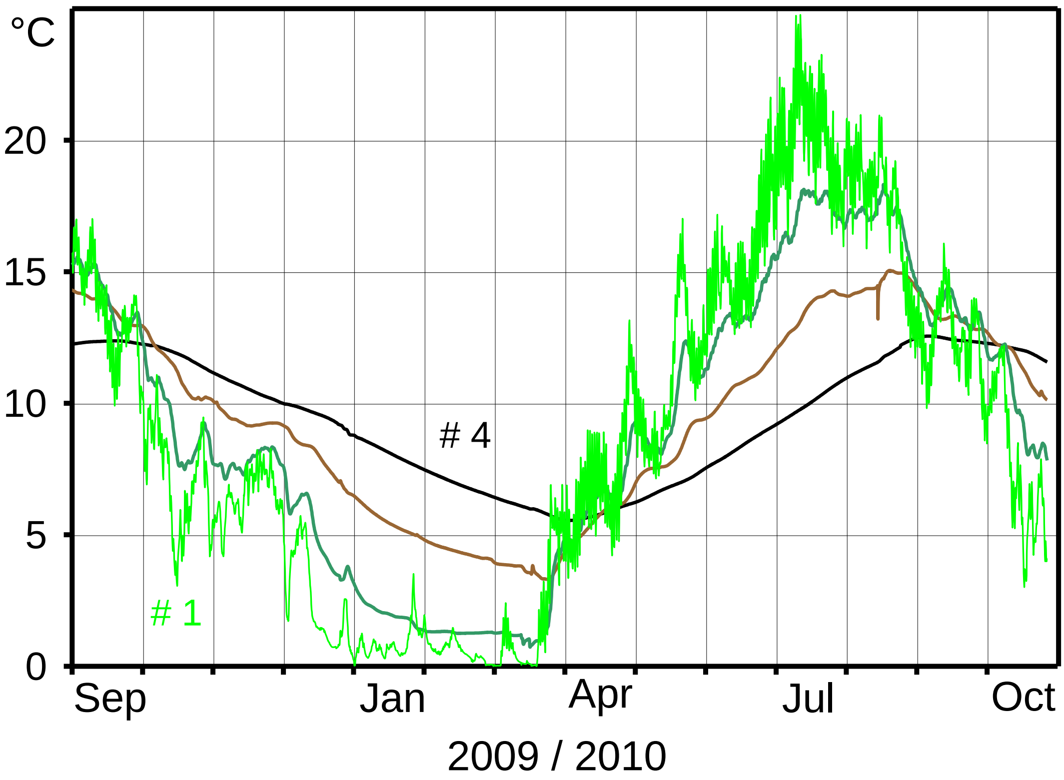


Fig. 8.7. Vejle ground temperature profile, at the centre of the building (Hall A). Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

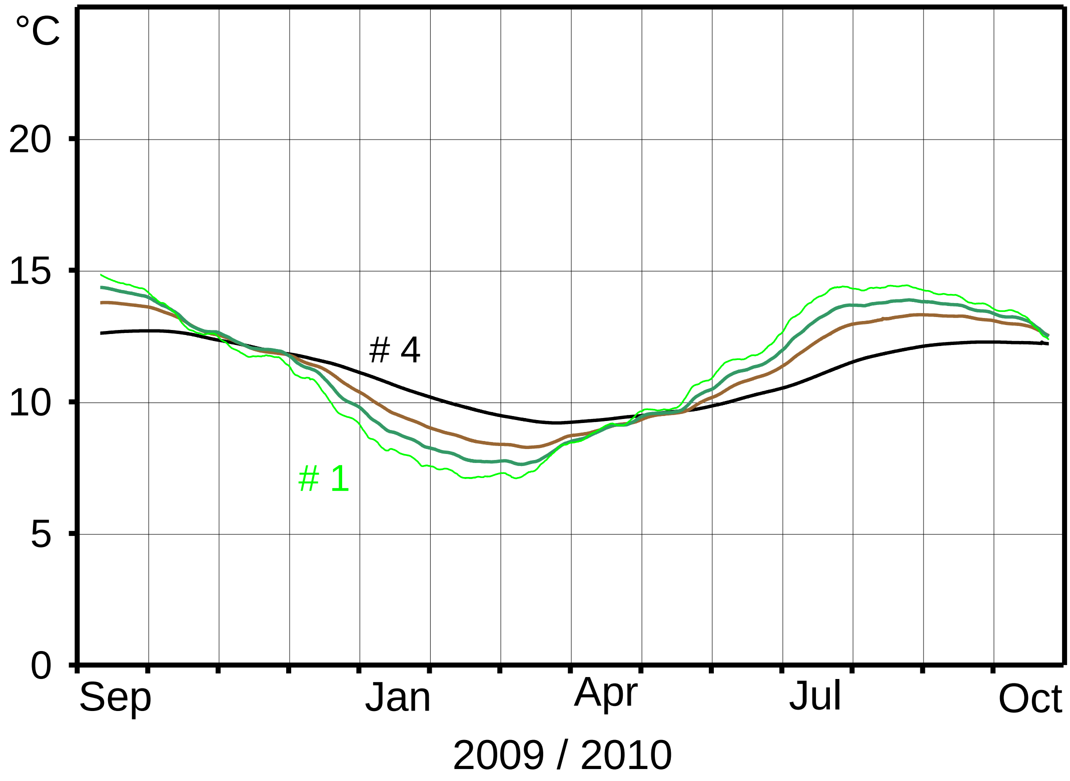


Fig. 8.8. Vejle ground temperature profile, at the edge of the building (Hall C). Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

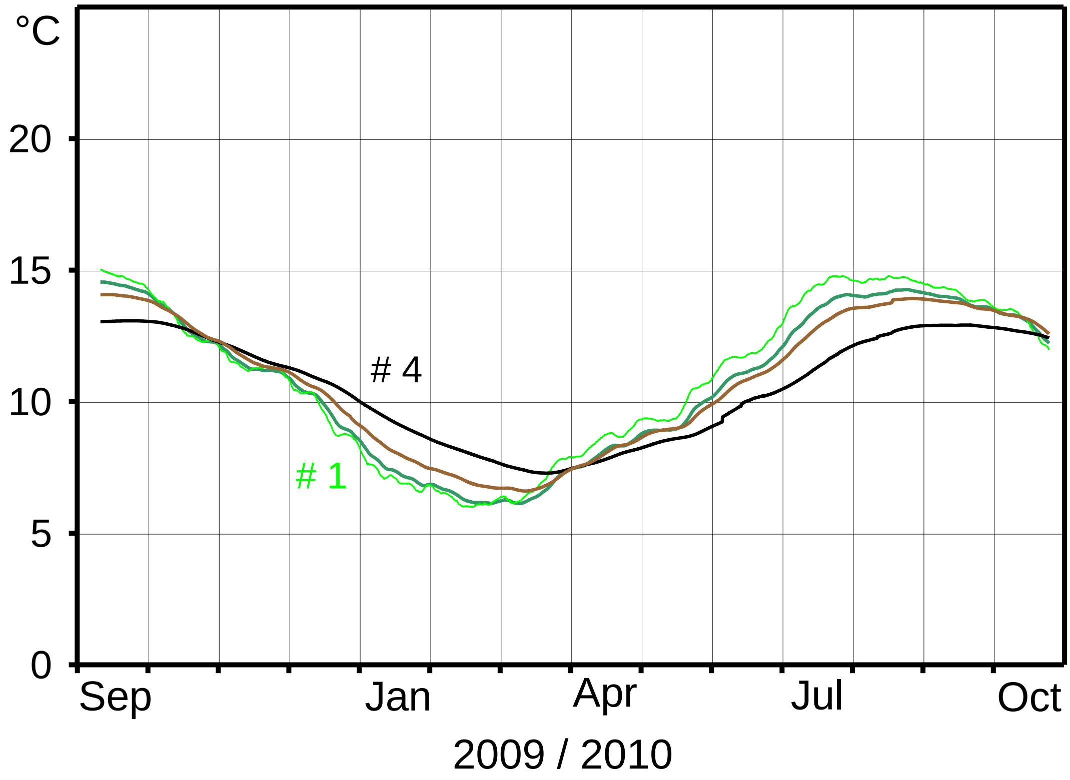


Fig. 8.9. Vejle ground temperature profile, outdoors. Temperature at -0.1 m (light green, thin curve #1), -0.2 m (dark green), -1 m (brown), and -2 m (black curve #4).

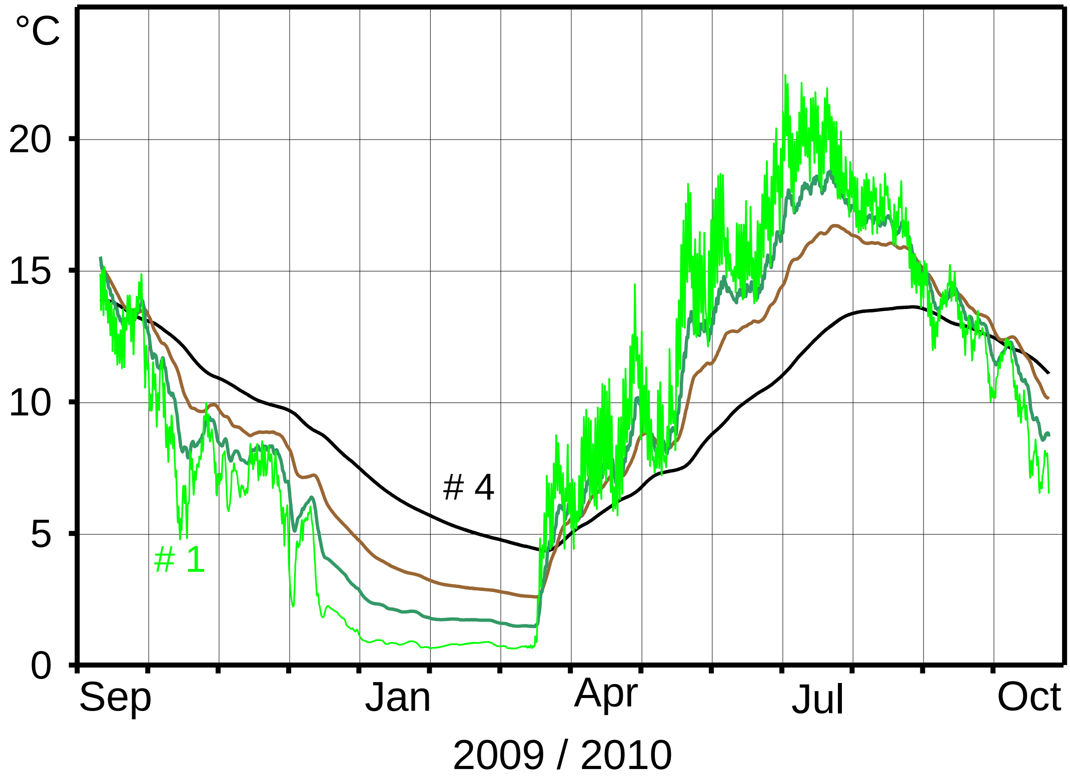
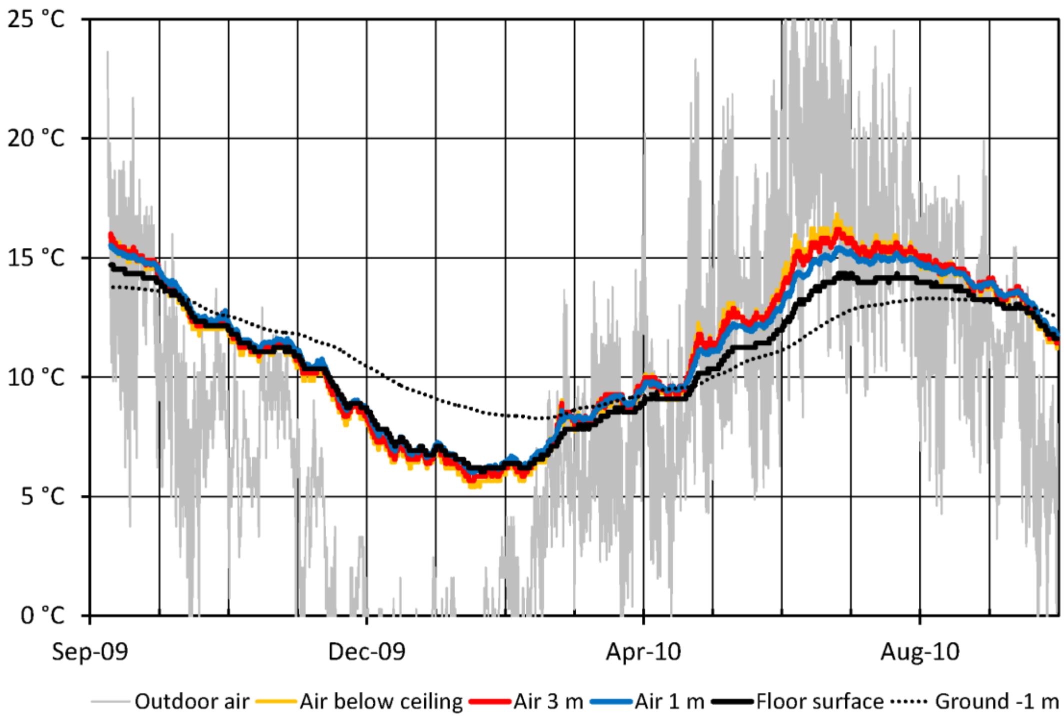


Fig. 8.10. Vejle air temperature profile, at the centre of the building (Hall C). Temperature at the Floor surface, 1 m, 3 m, and 5.8 m height. The top sensor was 0.5 m below the ceiling. Superimposed in the diagram are the outdoor air, and ground temperature (-1 m) at the centre of the building (Hall A).



8.3 Process air: Air flow rates and temperature

8.3.1 Ribe (March 23, 2010)

Temperature difference and air flow measured in the air ducts for basic climate storage room, before and after the dehumidifier unit:

Air flow measured by anemometer in duct: 0.346 m^3/s (1250 m^3/hour)

Temperature measured by anemometer's thermal sensor (recirculation fan on, dehumidifier off):

- Exhaust (air from store room): 11.0 °C
- Inlet (air returning to store room): 12.4 °C
- Temperature difference (inlet – exhaust): 1.40 °C

At the same time: Temperature read from display on ventilation system:

- Exhaust (air from store room): 10.8 °C
- Inlet (air returning to store room): 11.9 °C
- Temperature difference: 1.04 °C

Temperature difference measured using Multimeter (Agilent) with thermocouple sensors. Difference measured in duct: after and before dehumidifier, either with the dehumidifier turned off or on:

- Fan on, dehumidifier off: 1.63 °C difference
- Fan on, dehumidifier on for 30 min: 3.75 °C difference

8.3.2 Randers, (March 25, 2010)

Temperature difference and air flow measured in air ducts for basic climate storage room, before and after dehumidifier unit:

Air flow measured by anemometer in duct: 0.678 m^3/s (2440 m^3/hour)

Temperature measured by anemometer's thermal sensor (recirculation fan on, dehumidifier on):

- Exhaust (air from store room): 9.0 °C
- Inlet (air returning to store room): 13.4 °C
- Temperature difference (inlet-exhaust): 3.40 °C

Temperature difference measured using Multimeter (Agilent) with thermocouple sensors. Difference measured in duct, between after and before dehumidifier:

- Fan on, dehumidifier on for 30 min: 4.33 °C difference
- Fan on, dehumidifier on, and regeneration of desiccant on for 20 min: 10 °C difference (inlet air was approx. 20 °C, measured with anemometer)

8.4 Temperature increase in re-circulated air

In Ribe and Vejle the air temperature was monitored inside the ventilation ducts just before and after the dehumidifier and fan, as well as out in the storage room.

When the dehumidifiers were running, the air temperature inside the air handling system was typically raised by about 4-5 °C in the Ribe store, and by 2-3 °C in Vejle.

The temperature profiles of the storage room and the process air inside the air handling systems are shown in Figs. 8.11-8.12. For Ribe, the running time and the effect of the dehumidifier are also shown.

In Ribe the average temperature (for one year) was 11.9 °C inside the storage room, and 14.9 °C in the air handling system just after the fan and dehumidifier.

In Vejle the average temperature (for one year) was 11.5 °C inside the storage room, and 13.5 °C in the air handling system just after the fan and dehumidifier.

Fig. 8.11. Air temperature in the air handling system in the Ribe building: Storage room (black); in duct just before fan and dehumidifier (blue); in duct just after fan and dehumidifier (red). In green is shown the energy consumption of the dehumidifier.

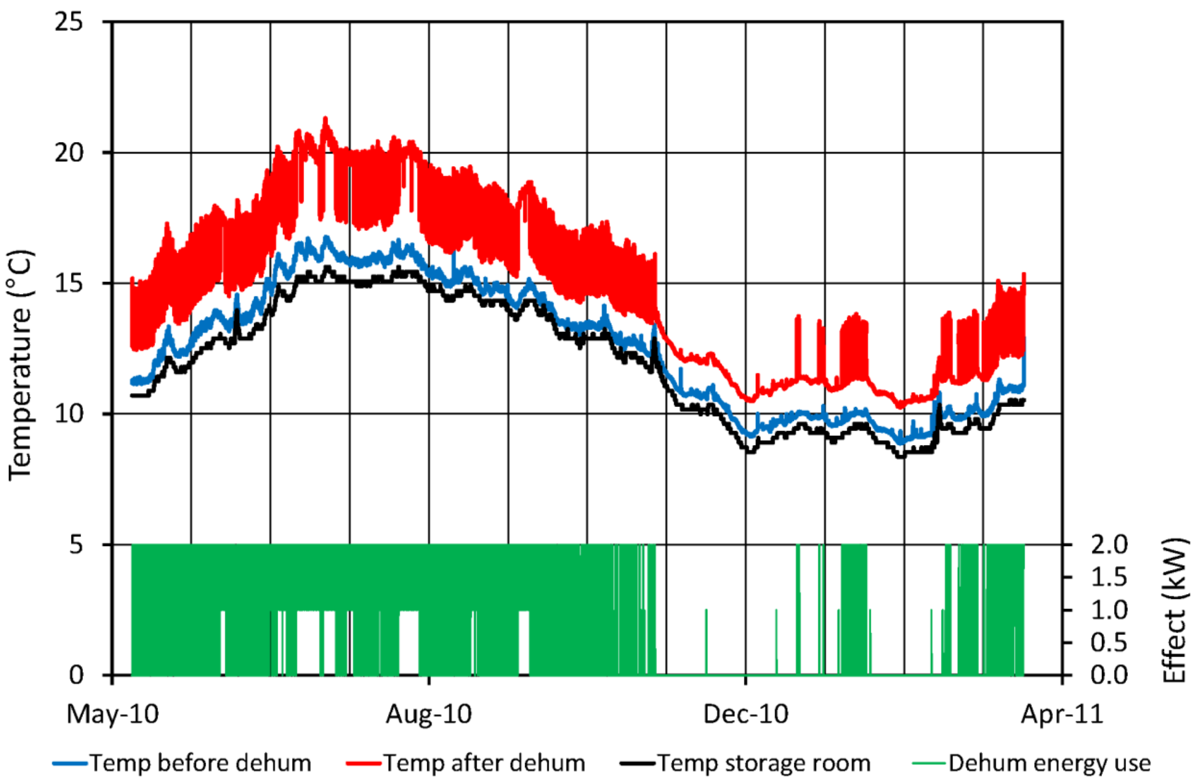
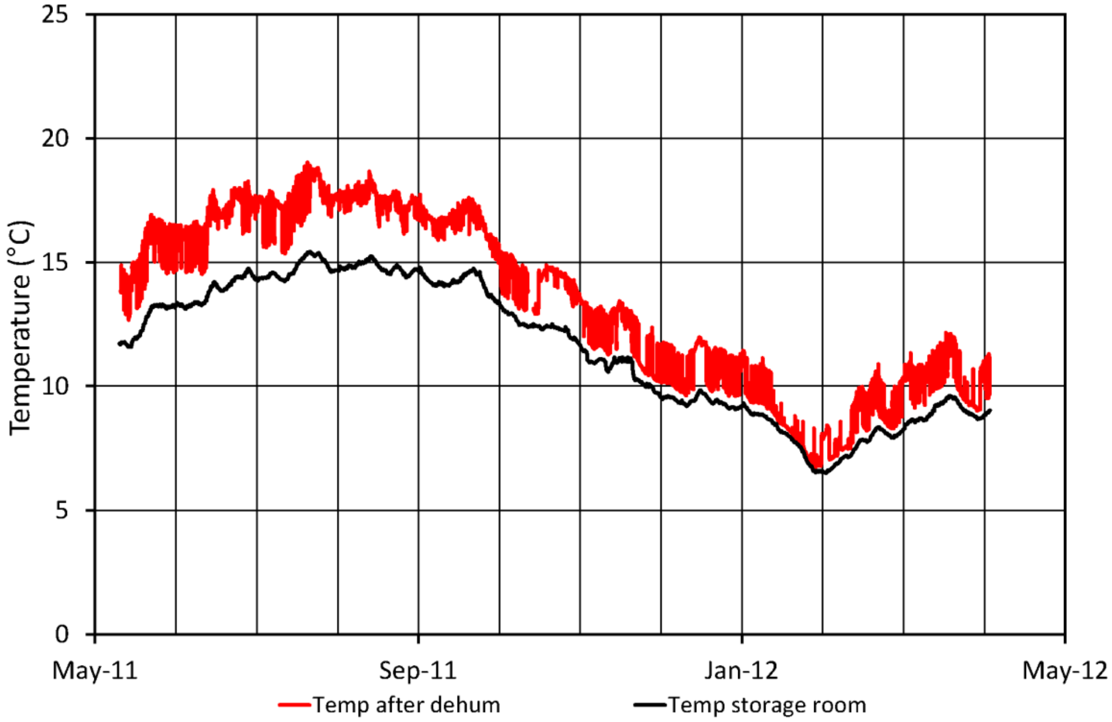


Fig. 8.12. Air temperature in the air handling system in the Vejle building: Basic storage room (black), and in duct just after fan and dehumidifier (red).



9. Additional sites

9.1 Music Museum (National Museum of Denmark)

Fig. 9.1. Inside the Music Museum storage room.

9.1.1 General information

The storage room belonging to the Music Museum is housed in an industrial building (previously a factory), in Søborg, Copenhagen. The building is shared among a number of companies, which each rent some storage space and/or room for workshops. The Music Museum storage room is a one-storey room of 300 m^2 (volume 1650 m^3). The storage room does not have any active climate control. The room is unheated; however, some indirect heating will leak into it from neighbouring heated areas (pseudo-passive heating). There is no mechanical humidity control. The humidity is to some degree controlled passively by the inner wall materials (cellular concrete) and by the materials stored in the room (e.g; wood). Due to a low air exchange rate and a slow, seasonal change in temperature, the relative humidity is kept in the moderate range (45 to 55 % RH).

9.1.2 Results

Table 9.1. Music Museum store: climate and energy (yearly statistics).

Year	**Temperature Average (Min – Max) [°C]**	**RH Average (Min – Max) [%]**	**TWPI [index]**	**Energy consumption total [kWh]**	**Energy consumption relative [kWh/m³ y]**	**Remarks**
2008	17 (9-25)	51 (45-55)	59	About 13,000	About 8	Effect of indirect heating estimated
2009	17 (7-28)	49 (43-53)	54			
2010	15 (6-27)	50 (44-58)	67			

Table 9.2. Music Museum store: ambient pollutants.

Pollutant	Indoor concentration [ppb] (± 1 STD)	**Indoor/Outdoor concentration ratio (± 1 STD)**
NO_2 (*)	4.6 (± 1.3)	**0.32 (± 0.11)**
O_3 (**)	1.2 (± 1.0)	**0.03 (± 0.01)**

(*) Average of 5 sampling periods

(**) Average of 3 sampling periods

Table 9.3. Music Museum store: indoor generated pollutants.

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
April-May 2009	3.6 (± 1.1)	5.1 (± 1.1)	**8.8 (± 2.2)**	18
June-July 2009	30 (± 7.8)	13 (± 0.74)	**44 (± 8.6)**	25
Aug-Sep 2009	15 (± 11)	12 (± 1.3)	**27 (± 13)**	23
Oct-Nov 2009	2.0 (± 1.8)	4.0 (± 1.6)	**6.0 (± 3.5)**	13
Dec-Jan 2010	6.1 (± 4.3)	3.3 (± 0.42)	**9.4 (± 4.7)**	8
Feb 2010	3.5 (± 0.92)	1.6 (± 0.42)	**5.1 (± 1.3)**	8

9.1.3 Music Museum: air exchange rate

The air exchange rate was measured on one occasion (27 March – 1 April 2009) by the simple concentration decay method (using CO_2): <u>0.06 per hour</u>.

9.2 Værløse Shelter 209 (National Museum of Denmark)

Fig. 9.2. Shelter 209 storage building.

9.2.1 General information

The National Museum of Denmark rents three former aircraft hangars ('shelters') at the now-closed Værløse airfield, north of Copenhagen. Each aircraft shelter is a superstructure made of 0.5 m solid reinforced concrete walls and roof, on a concrete floor with a large and heavy steel door at the front. There are no windows or additional openings in the building envelopes. The buildings have no thermal insulation. The shape of the building is not exactly rectangular but allows for the housing of one fighter jet plane (Fig. 9.2). The volume is approximately 2000 m^3. The shelters are unheated, but mechanically dehumidified to a set-point of 50% RH. Each shelter is fitted with three Munters M120 desiccant-dehumidifies.

9.2.2 Results

Table 9.4. Værløse 209: climate and energy (yearly statistics).

Year	Temperature Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy consumption total [kWh]	Energy consumption relative [kWh/m^3 y]	Remarks
2009	11 ((-1) - 26)	52 (47-58)	86	-	-	Energy not measured
2010	11 ((-1) - 27)	53 (47-62)	84	10520	5.2	
2011	12 (0 - 24)	54 (48 - 66)	83	12720	6.4	

Table 9.5.Værløse Shelter 209: indoor generated pollutants.

Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
January 2011	5.2 (± 0.55)	0.73 (± 0.15)	**5.9 (± 0.68)**	3
July 2011	13 (± 0.83)	10 (± 0.71)	**23 (± 1.2)**	21

9.2.3. Værløse Shelter 209: air exchange rate.

The air exchange rate was measured on two occasions (summer and winter) by the simple concentration decay method (using CO_2):

- 14-16 June 2010: 0.03 per hour.
- 12-15 January 2011: 0.05 per hour.

9.3 Arnamagnæan Institute (University of Copenhagen), manuscript archive

Fig. 9.3. Left: University of Copenhagen, Amager Campus. The archive is located on the second floor, behind the part of wall with no windows. Right: inside the archive.

9.3.1 General information

The manuscript archive at the Arnamagnæan Institute, University of Copenhagen, is a small (40 m^2; 120 m^3) room located on the second floor of a university office building. The archive houses manuscripts on parchment and paper, which are stored in boxes or bound into books. The climate inside the archive is controlled by buffered conservation heating. The heating is performed pseudo-passively, by the leaking heat from the adjacent corridors and rooms, which are maintained at a comfortable temperature. The winter temperature outside is allowed to influence the archive temperature through thin insulation on the two outside walls, and thicker insulation on the walls towards the interior. As a consequence, the temperature of the archive is maintained about midway between the inside temperature of the whole building, which is always about 22°C, and the varying outdoor temperature. This, combined with the humidity buffering by the wall materials and by the archival boxes etc., ensures a steady relative humidity, even though the water vapour concentration is different from that outside over long periods. Fine tuning of the relative humidity is achieved through pumping in outside air when, by chance, it has the right water vapour concentration to correct the inside relative humidity. This is done by a small mechanical ventilation unit (fan effect: 70W).

9.3.2 Results

Table 9.6. Arnamagnæan Institute: climate and energy (yearly statistics).

Year	**Temperature Average (Min – Max) [°C]**	**RH Average (Min – Max) [%]**	**TWPI [index]**	**Energy consumption total [kWh]**	**Energy consumption relative [kWh/m³ y]**	**Remarks**
2007	18 (15-23)	53 (48-58)	47	About 1700 (heat: 1560) (fan: 140)	About 14	Indirect heating, flux calculated. Fan measured (2010)
2008	19 (15-24)	53 (50-56)	44			
2009	19 (14-23)	54 (51-56)	45			
2010	19 (14-24)	52 (48-55)	48			

Table 9.7. Arnamagnæan Institute: ambient pollutant (One sampling period only).

Pollutant	Indoor concentration [ppb] (± 1 STD)	**Indoor/Outdoor concentration ratio** (± 1 STD)
NO_2	1.9 (± 0.06)	**0.07** (± 0.01)
O_3	1.3 (± 1.1)	**0.06** (± 0.05)

Table 9.8. Arnamagnæan Institute: indoor generated pollutants.

Organic acids Sampling period	Formic acid concentration [ppb] (± 1 STD)	Acetic acid concentration [ppb] (± 1 STD)	**Organic acids concentration (total) [ppb] (± 1 STD)**	Mean temperature during sampling [°C]
Oct 2009	1.0 (± 0.00)	2.0 (± 0.10)	**3.0 (± 0.10)**	20
May 2010	0.70 (± 0.07)	2.0 (± 0.28)	**2.7 (± 0.35)**	19
Aug 2010	0.50 (± 0.00)	1.6 (± 0.51)	**2.1 (± 0.51)**	22
Nov 2010	0.63 (± 0.19)	0.52 (± 0.01)	**1.2 (± 0.19)**	16
Feb 2011	0.99 (± 0.29)	0.51 (± 0.01)	**1.5 (± 0.30)**	15

9.3.3 Arnamagnæan Institute: air exchange rate.

The air exchange rate was measured on two occasions (winter and summer) by the PFT method using one tracer gas (one zone). During the winter period measurement (3-20 December 2010) the ventilation system was only running for 5 hours, thus it was off more than 98% of the time:

- 3-20 December 2010: 0.04 per hour.
- 27 June - 13 July 2011: 0.06 per hour.

The running time of the ventilation system was monitored continuously for more than one year. During the 365 days of 2010 the fan was on for 23% of the time. The running time per month is shown in Table 9.9.

In a previous study[6] the rate of fresh air delivered directly by the ventilation system, when running, was measured using a hot-wire anemometer to be about 30 m^3/hour (which will account for a forced ventilation rate of 0.25 $hour^{-1}$).

Table 9.9. Arnamagnæan Institute: Running time (%) of the archive's ventilation system for 2010.

Month	Fan running time [%]
January	0.0
February	0.0
March	8.4
April	6.7
May	21
June	51
July	41
August	36
September	48
October	40
November	23
December	0.7
All 2010	***23***

[6] Ryhl-Svendsen, M., 2007: *Air quality in museum storage buildings*. PhD-Thesis, School of Conservation, Royal Danish Academy of Fine Arts.

9.4 Other sites

Energy and climate data were acquired from several additional Danish storage facilities (museums, libraries, archives), which had a large variation in the type of climate control systems applied, as well as in the size and contents of the collection (Table 9.10).

The energy data was mainly collected by recording the energy meters of the buildings (where possible), while climate data was collected from various building managements systems (where possible) or from local data logger equipment. Some values were estimated rather than measured, and in general there is a high degree of uncertainty connected to the "other sites" data.

Fig. 9.4. Cooled archive (5°C) at the Danish Film Institute: Box G for storage of acetate materials.

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Table 9.10. Annual climate and energy statistics, other sites.

Note in table: (*) Typically: 18-20 °C and 50% RH. Ref: BS5454, 2000: Recommendations for the storage and exhibition of archival documents. British Standards Institute, London.

Building	Year	Volume [m³]	Temp Average (Min – Max) [°C]	RH Average (Min – Max) [%]	TWPI [index]	Energy use, total [kWh]	Energy use, relative [kWh/m³ y]	Remarks
National Museum of DK Brede Building 9 Room 228 (Basic climate) Kgs. Lyngby	2010	1995	16 (7-23)	52 (43-59)	61	63,432 (total system)	8.2	Part of a 7700 m³ facility with one shared HVAC system. Old but retro-fitted building. Ventilation provides a constant overpressure in rooms.
The Royal Library Book Stack #1 Amager	2007	14500	18-23	c. 50	c. 45	404,000	28	Full HVAC, modern building. Set-point aims for BS5454 specifications (*).
Iron Mountain Archive Avedøre	Sep. 2009 -Aug. 2010	44700	19 (16-25)	54 (39-72)	43	412,790 (estimate)	15 (estimate)	Energy consumption estimated. Modern building, HVAC (no cooling). Set-point aims for BS5454 specifications (*).
Moesgaard Museum External storage hall Aarhus	Climate data: 2012 Energy data 2008-2011	2800	14 (7-24)	56 (35-68)	70	26,000	9.3	Industrial-style lightweight building, moderate thermal insulation (150 mm), mechanical dehumidification
Danish Film Institute Acetate storage (Box G) Glostrup	2007	2276	5	40	393	67,500	30	Constantly cooled and dehumidified. Modern facility.
Danish Film Institute Nitrate storage vault Hillerød	2007	2400	- 5	30	2300	600,000	250	Constantly cooled and dehumidified. Modern facility.

Building	**Year**	**Volume [m³]**	**Temp Average (Min – Max) [°C]**	**RH Average (Min – Max) [%]**	**TWPI [index]**	**Energy use, total [kWh]**	**Energy use, relative [kWh/m³ y]**	**Remarks**
Royal Danish Arsenal Museum. Bunker storage room Copenhagen area	Climate data: 2002 Energy data 2005-2009	397	9 (2-17)	38 (31-43)	201	3,661	9.2	Set-point 40% RH Mechanical dehumidification, store is partly underground.
Royal Danish Arsenal Museum. Bunker storage room Copenhagen area	2005-2009	397 (each)	9 (2-17)	c. 45	165	2,207	5.6	Set-point 45% RH Mechanical dehumidification, store is partly underground. Average of data from six equal size storage rooms
Royal Danish Arsenal Museum. Bunker storage room Copenhagen area	2005-2009	397 (each)	9 (2-17)	c. 50	150	1,273	3.2	Set-point 50% RH Mechanical dehumidification, store is partly underground. Average of data from two equal size storage rooms

10. Outdoor climate

10.1 Weather stations

For the four main sites ambient climate data was supplied from the Danish Meteorological Institute (DMI), from the weather stations located closest to each site. These data sets covered the monitoring period until end of 2009. For Ribe, Vejle and Ørholm, local weather stations were installed on the premises for continued monitoring (see Methods: Outdoor climate, Chapter 11.4).

Below, the ambient climate is summarized in monthly average values for temperature and relative humidity for two selected locations. They represent east and west Denmark, for the period 2007-2010 (Tables 10.1-10.2).

For east Denmark the DMI data represent measurements at Sjælsmark Kaserne north of Copenhagen (2007-2009). This weather station is located about 9 km from Ørholm. The data shown for 2010 was collected on-site in Ørholm.

For west Denmark the DMI data represent measurements at Esbjerg Airport (2007-2009). This weather station is located approximately 25 km from Ribe and 65 km from Vejle. The data shown for 2010 was collected on-site in Ribe.

10.2 Summary of ambient climate

For the period 2007-2010 the climate varied from year to year. The year 2007 was a record warm year with the highest annual temperature average yet measured in Denmark (9.5 °C compared to 7.7 °C for a normal year). Also 2008 and 2009 were warm years compared to normal. The year 2010 was colder than normal; especially during winter (annual average 7.0 °C).

To illustrate the variation between the individual years 2007-2010 and a "typical" year, a summary of the artificial Danish Reference Year (DRY) [7] is shown in Table 10.3.

[7] J.M. Jensen, J.M., Lund, H., 1995: *Design Reference Year, DRY - Et Nyt Dansk Referenceår*. Meddelelse nr. 281, Laboratoriet for Varmeisolering, Danmarks Tekniske Universitet, Lyngby.

Table 10.1: East Denmark: Monthly climate averages

* = Sjælsmark Kaserne (DMI) ; †=Ørholm Storage Facility

T [°C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007 *	4.4	1.5	6.2	9.0	12.3	16.4	15.8	17.1	12.8	8.1	4.8	3.4
2008 *	3.7	4.4	3.3	7.3	12.0	15.1	17.7	16.8	12.9	9.3	5.7	2.5
2009 *	0.4	0.0	3.3	9.5	11.7	14.0	17.7	17.5	14.1	7.2	7.0	0.7
2010 †	-3.4	-1.7	2.5	7.1	10.0	11.7	19.7	16.8	12.5	7.8	2.9	-4.3

RH [%]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007 *	89	90	80	71	78	79	84	83	87	89	88	94
2008 *	91	85	83	78	71	71	75	84	86	91	91	96
2009 *	91	92	86	71	76	77	82	80	83	87	93	90
2010 †	95	97	91	81	82	80	74	84	85	87	91	91

Table 10.2: West Denmark: Monthly climate averages

* = Esbjerg Airport (DMI) ; †= Ribe Storage Facility

T [°C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007 *	5.8	3.1	6.6	9.8	11.2	16.0	15.9	16.7	13.1	8.7	5.6	3.9
2008 *	4.4	4.8	3.9	7.4	12.8	15.2	17.2	16.6	12.9	10.3	6.2	2.9
2009 *	1.1	1.7	4.4	9.9	11.4	13.8	17.0	17.1	14.0	8.2	7.7	1.4
2010 †	-3.3	-1.5	3.1	7.6	9.4	14.2	18.7	15.9	12.7	8.9	2.8	-4.7

RH [%]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007 *	83	88	77	72	79	77	80	78	81	84	83	90
2008 *	86	84	81	77	63	68	73	80	81	83	85	90
2009 *	89	89	86	73	74	71	77	76	79	81	88	90
2010 †	94	94	93	80	82	82	81	88	80	77	82	80

Table 10.3: Danish Reference Year (DRY): Monthly climate averages

DRY	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T [°C]	-0.5	-1.0	1.7	5.6	11.3	12.4	16.4	16.2	12.5	9.1	4.8	1.5
RH [%]	89	85	81	80	73	75	80	76	87	81	91	83

11. Methods and equipment

11.1 Air temperature and relative humidity

The indoor climate (temperature and RH) was monitored either by sensors connected to the local building management system, or to independent data loggers. This type of sensors is generally recognized to have an accuracy of +/- 3 %RH and +/- 0.5 °C. In each storage room the sensors were placed on storage shelves, walls or pillars and well away from outer walls, typically at 1.5 – 2.5 m above floor level.

Ribe: In the storage rooms IPI Preservation Environment Monitors (PEM) dataloggers were used. Additional short-term measurements in special locations (attic, depot, staff area, etc.) were carried out with Gemini Tinytag Plus 2 climate dataloggers (Model TGP 4500). Measurements were recorded at 30 min intervals. Monitoring period: December 2005 – April 2011.

Vejle: The indoor climate (temperature and RH) was monitored in each storage room by a system of climate sensors connected to wireless transmitters (Hanwell ML 2000). Measurements were recorded at 10 min intervals. Monitoring period: March 2005 – April 2011.

Randers: The indoor climate (temperature and RH) was monitored in each storage room using the installed building management system sensors (Hanwell ML 2000 temperature and RH wireless transmitters). Measurements were recorded at 5 min intervals. Monitoring period: November 2008 – April 2011.

Ørholm: The indoor climate (temperature and RH) was monitored in each hall using sensors connected to the local building management system (BMS), as well as by IPI Preservation Environment Monitors (PEM) dataloggers. Measurements were recorded at 30 min intervals. For this report PEM data from the centre hall (room P2) was used. Monitoring since 1999 by BMS sensors and in addition since October 2004 by PEM dataloggers (ongoing).

11.2 Air temperature gradient

Measurements of air temperature at different heights were conducted using Gemini Tinytag Talk temperature dataloggers (model Tinytag Talk 4014). Furthermore, the temperature at the floor surface was measured using a datalogger with an external temperature probe (model Tinytag Talk 4023). The sensors have an accuracy of +/- 0.4 °C. The sensors were placed at floor level (probe glued onto the floor) and at 1.0 m and 3.0 m above floor, and at 0.5 m below the ceiling. Below ceiling was in Ribe at a height of 5.7 m, Vejle 5.8 m, Randers 6.4 m, and Ørholm 8.2 m above the floor. Measurements were recorded at 3 hour intervals. This series of measurements was for all of the sites only conducted in the basic climate storage area, and approximately in the centre of the store. Monitoring period for all sites was September 2009 – April 2011.

11.3 Process air

The temperature of the process air going through the air handling system was monitored in Ribe and Vejle for one year (Ribe: May 2010 – April 2011; Vejle: April 2011-April 2012). Measurements were taken in the centre of the ventilation duct before and after the fan and dehumidifier, assuming that the "before" air approximated the general air temperature inside the storage room, and the "after" air approximated the temperature of the conditioned air when returned back into the store. Measurements were made using a Gemini Tinytag temperature datalogger (Model TGP 4520), with two external temperature probes (standard thermistor probe, model PB-5001), which were inserted into the centre of the duct through a small hole. The sensors have an accuracy of +/- 0.2 °C. Measurements were recorded at 15 min intervals.

The temperature difference of the process air was monitored in Ribe and Randers for one day (Ribe: 23 March 2010; Randers: 25 March 2010). For this an Agilent 34405A 5½ digit multi-meter was used, with two external temperature probes (thermocouple, type K), which were inserted into the centre of the duct through a small hole. The sensors were calibrated to give a signal of 0.040 mV per one degree Celsius difference. At the same time, the airflow and temperature through the air handling system was measured using a Testo 425 anemometer for the measurement of the air speed inside the ducts. The probe has an accuracy of +/- 0.03 m/s and +/- 0.5 °C. Process air measurements were only conducted for the basic climate storage area.

Airflow in the ventilation ducts were measured in Ribe and Randers. In Vejle, the air flow rates for the dry and basic climate zones were estimated from the design description of the air handling system.

11.4 Outdoor climate

For reference, the outdoor air temperature and relative humidity were monitored at all sites, in parallel with the indoor climate measurements:

Ribe: A battery-driven datalogger (Onset HOBO H08-Pro) was mounted inside a rain and solar shield, and located on the north side of a garden tool shed near the museum storage building at about 3 m above ground. Measurements were recorded at 30 min intervals.

Vejle: Data was collected from a weather station on the roof (connected to the building management system), as well as from a battery-driven Onset HOBO U23 Pro v2 datalogger placed on a 2 m pole in a rain and solar shield, about 40 m from the building on an open grass lane, but near small trees. The datalogger measurements were recorded at 30 min intervals

Randers: Data was collected from a weather station on the roof connected to the building management system. Measurements were recorded at 5 min intervals.

Ørholm: A battery-driven datalogger (Onset HOBO U23 Pro v2) was mounted inside a Stevenson screen at 1.8 m height, and located more than 35 m from the building. The screen is placed on an open grass lane, however, with several trees in the vicinity. Measurements were recorded at 30 min intervals.

For all outdoor sensors, an accuracy of +/- 3% RH and +/- 0.2 °C is assumed.

Furthermore, weather data have been acquired from the Danish Meteorological Institute for weather stations close to all sites for the periods: monitoring period start (individual) until 31-12-2009.

11.5 Ground temperature

Soil temperature at varying depths below the storage buildings and outdoors next to the buildings was measured in Ribe, Vejle and Ørholm. Monitoring was carried out using Gemini Tinytag temperature dataloggers (model TGP 4520) with external temperature probes (flexible thermistor probe, model PB-5006-3M). The probes were attached to a thin carbon fiber rod at distances which ensured the correct depth from the surface of the ground/floor, and lowered into a 30 mm diameter and 2 m deep hole made by drilling through the concrete floor (indoors) and then driving a metal pipe down through the soil and removing it again. The holes were filled again by watering down excess soil and extra sand around the temperature probes, and indoors the hole was sealed with concrete. The sensors were located at 0.1 m, 0.5 m, 1 m and 2 m below surface. Indoors, the 0.1 m sensor was cast into the concrete which sealed off the hole in the floor. Outdoors the 0.1.m sensor was located just below the grass turf. Measurements were recorded at 3 hour intervals. Ground temperature measurements were only conducted in the basic climate storage areas, but at two locations: inside the storage room approximately in the centre of the building, and at the edge; 1 m from the outer wall (in Ribe: south-east wall; Vejle: south-west; Ørholm: south-east).

The outdoor measurement location (undisturbed ground) was in Ribe located more than 30 m from the building on an open grass lane, in Vejle about 40 m from the building on an open grass lane, but near small trees, and in Ørholm more than 35 m from the building on an open grass lane but with several trees in the vicinity.

Monitoring has been conducted at all sites since September 2009, and is still ongoing except at Ribe (ended September 2012).

11.6 Energy consumption

Typically the consumption of electricity for each dehumidifier and fan was monitored separately for each individual unit and for each storage area (e.g.; basic and dry climate zone).

<u>Ribe:</u> Energy use was recorded for each dehumidifier using a Merlin Gerin ME4rz kilowatt hour meter with a Gemini Tinytag Plus TGPR-1201 datalogger, which recorded and time-stamped one impulse for each 1 kWh consumed. The annual energy consumption of the ventilation fans, which run continuously, was for the first year estimated from the effect given in the technical description of the units, and from 2008 monitored by a Dent Elite Pro recording poly phase power meter with extended memory, logging energy use by use of clamp-on current transformers and direct voltage measurement. Furthermore the energy meters of the building were manually read during site visits approximately every six months. Monitoring period was November 2007 – April 2011.

<u>Vejle:</u> The consumption of electricity for each dehumidifier was recorded using a Merlin Gerin ME4zr kilowatt hour meter, which gave out one impulse for each 10 kWh consumed. The impulses were recorded and time-stamped by a Gemini Tinytag Plus TGPR-1201 datalogger. Ventilation fans were monitored by a Dent Elite Pro recording poly phase power meter with extended memory, logging energy use on all three phases by use of clamp-on current transformers and direct voltage measurement. Heating of the dry climate storage room was monitored by a Kamstrup Multical 601 Ultraflow meter. Monitoring period was November 2006 – April 2011, however, ventilation data were only recorded in 2007.

Randers: The consumption of electricity for each dehumidifier plus other processes was recorded manually from the building's energy meters. Records were taken by the staff approximately once per week. Monitoring period was October 2008 – April 2011.

Ørholm: The consumption of electricity for air conditioning was recorded using a Kamstrup 351 Combi kilowatt meter connected to the Building Management System, which recorded and time-stamped one impulse for each 10 kWh consumed. Monitoring since December 2009 (ongoing). Energy consumption for heating (hot water element) was not monitored.

Arnamagnæan Institute: The running time of the ventilation fan was monitored using a Dent MAGlogger, which recorded the on and off time for the ventilation fan (measuring the internal magnetic field). Monitoring period was October 2009 – January 2011. The fan effect was read from the technical specification of the component (70W), not measured.

Værløse Shelter 209: The consumption of electricity for dehumidification was recorded using a Merlin Gerin ME4zr kilowatt hour meter, which gave out one impulse for each 10 kWh consumed. The impulses were recorded and time-stamped by a Gemini Tinytag Plus TGPR-1201 datalogger.

11.7 Air exchange rate

Ribe, Randers, Vejle and Ørholm:

The rate of air exchange with ambient air was measured on two occasions; in March/April 2010 and November 2010 using the per-fluorocarbon tracer (PFT) method based on tracer gas release from permeation tubes and re-sampling the tracer gas(es) on adsorber tubes. Through the use of two different tracer gases, the interchange of air between two indoor zones (two storage rooms) could be quantified, as well as the overall air exchange rate with the ambient. The sampling kit and subsequent analysis were provided by The Danish Building Research Institute (SBi), Hørsholm, Denmark [8].

For Ribe, Randers and Vejle, two different tracer gasses were used for the basic and dry storage areas (for all details see Appendix: reports from SBI). In Ørholm only one tracer gas was used, as there was only one climate zone.

In Ribe, on one occasion (24-30 June 2008), the air exchange rate of the basic climate store was measured by the simple concentration decay method: CO_2 gas was released from a compressed gas cylinder and mixed into the room air with electrical fans, for the subsequent measurement of the gas concentration decay using a Vaisala CO_2 sensor with a Gemini Tinytag TGPR-0704 datalogger. Data logging intervals were 1 min.

The simple concentration decay method provides a short term measurement which gives the instant air exchange rate during a few hours or days, while the PFT method provides a measure of the average air exchange rate during a longer measurement period; in this case about four weeks.

[8] Bergsøe, N.C., 1992: Passiv sporgasmetode til ventilationsundersøgelser. Beskrivelse og analyse af PFT-metoden. (Passive tracer gas method for ventilation investigations. Description and analysis of the PFT-method), SBI report 227, Danish Building Research Institute, Hørsholm.

Other locations:

At the Arnamagnæan Institute, the air exchange rate was measured twice by the PFT method (one zone).

The simple concentration decay method (with CO_2) was used for establishing the air exchange rate of the Music Museum storage room, and for Værløse Shelter 209.

11.8 Air pollution sampling

Nitrogen dioxide was sampled using a diffusion sampler (Palmes tube type), impregnated with triethanolamine and subsequently analysed colorimetrically for the production of nitrite using UV-Vis-spectrophotometry. The preparation and analysis was carried out in-house at the laboratory of the National Museum's Conservation Department.

Ozone was sampled using a diffusion sampler (Palmes tube type). The samplers and subsequent analysis were provided by Gradko International Ltd., United Kingdom.

Ammonia was sampled using a diffusion sampler (Palmes tube type). The samplers and subsequent analysis were provided by Gradko International Ltd., United Kingdom.

Hydrogen sulphide was sampled using a diffusion sampler (Palmes tube type). The samplers and subsequent analysis were provided by Gradko International Ltd., United Kingdom.

Formic and Acetic acid were sampled in combination using a diffusion sampler (Ferm-badge type). The samplers and subsequent analysis were provided by the Swedish Environmental Institute (IVL).

All sampling periods were approximately four weeks, and all compounds were sampled in duplicate (two samplers at each location). For each sampling period the reported concentration is therefore the average result of two simultaneous measurements. Indoor sampling took place with the samplers mounted on an aluminium rack with metal spring clips in a location out in open air and away from large surfaces (e.g., walls or large objects). At each site the indoor sampling location was placed approximately in the middle of the basic climate storage room. Outdoor sampling took place in the vicinity of each building, e.g. with samplers mounted on a nearby lamp post. All outdoor samplers were mounted by metal spring clips on a rack under a white sun-and-rain cover.

12. Publications

The project has resulted in a large number of presentations and publications, in journals and at international conferences. Below is a list of publications, which originate directly from the field work described in this report, as well as a selection of related work, which was carried out also during the UMTS Project.

12.1 Journal articles

Larsen, P.K., Jensen, L.Aa., Ryhl-Svendsen, M., Padfield, T. (2009): Museumsbygninger med lavt energiforbrug. *Nationalmuseets Arbejdsmark* 2009, pp. 121-136.

Ryhl-Svendsen, M., Jensen, L.Aa., Larsen, P.K., Padfield, T. (2010): Does a standard temperature need to be constant? *Meddelelser om Konservering* 1/2010, pp. 13-20. *(With peer review)*

Larsen, P.K., Ryhl-Svendsen, M., Bøhm, B., Jensen, L.Aa. (2011): Museumsmagasiner med lavt energiforbrug. *HVAC Magasinet* 4 (April), pp. 76-81.

Bøhm, B., Ryhl-Svendsen, M. (2011): Analysis of the thermal conditions in an unheated museum store in a temperate climate. On the thermal interaction of earth and store. *Energy and Buildings* 43, pp. 3337-3342. *(With peer review)*

Ryhl-Svendsen, M. (2012): Ophedet debat eller tørre argumenter? Den nye diskussion af museers klimakrav. *Danske Museer* 3/2012, pp. 27-30.

Alling, A., Ryhl-Svendsen, M. (2012): Hvad er indeklimaet i en flyttekasse? *Meddelelser om Konservering* 1/2012, pp. 31-33.

Larsen, P.K., Ryhl-Svendsen, M., Jensen, L.Aa., Bøhm, B., Padfield, T. (2012): Konstantes Raumklima und niedriger Energieverbrauch - kein Widerspruch. Zehn Jahre Erfahrung mit energieeffizienter Klimatisierung in Archiven und Museumsmagazinen. *RESTAURO* 7/2012, pp. 53-60.

12.2 Conferences

Padfield, T., Larsen, P.K., Jensen, L.Aa., Ryhl-Svendsen, M., (2007): The potential and limits for passive air conditioning of museums, stores and archives. *Museum Microclimates*, 19-23 November 2007, National Museum of Denmark, Copenhagen, pp. 191-198. *(With peer review)*

Ryhl-Svendsen, M., Jensen, L.Aa., Larsen, P.K., Padfield, T. (2009): Does a standard temperature need to be constant? Talk presented at *Going Green: Toward Sustainability in Conservation*, British Museum, 24 April 2009 (published separately in the journal *Meddelelser om Konservering* 1/2010, op.cit.).

Ryhl-Svendsen, M., Jensen, L.Aa., Larsen, P.K., Bøhm, B., Padfield, T. (2010): Energy consumption of museum storage rooms and the quality of indoor climate. Talk presented at the *International Symposium on the future of Museum Climate seen in the context of Global Climate Change and Energy Priority*, Statens Museum for Kunst, 1 March 2010, Copenhagen (presentation only).

Ryhl-Svendsen, M., Jensen, L.Aa. (2010): Lav-energi museumsmagasiner. Talk presented at *Kulturhistorisk Orienteringsmøde*, Konserveringsfaglig Gruppe, Fuglsøcenteret, November 17, 2010 (presentation only)

Larsen, P.K., Padfield, T. (2011): The off-grid museum. Talk presented at the *Annual Meeting of the American Institute for Conservation of Historic and Artistic Works (AIC)*, Philadelphia, May 31 – June 1, 2011. Abstract in: *Ethos Logos Pathos: Ethical Principles and Critical Thinking in Conservation, 39th AIC Annual Meeting,* Book of Abstracts, p. 44. A full version of the lecture is available online: http://www.conservationphysics.org/musdes/low_energy_museum.pdf

Ryhl-Svendsen, M., Jensen, L.Aa., Larsen, P.K., Bøhm, B., Padfield, T., (2011): Ultra-low-energy museum storage. *ICOM-CC 16th Triennial Conference*, Lisbon 19-23 September 2011, ICOM Committee for Conservation, 8 pp (CD-ROM). *(With peer review)*

Ryhl-Svendsen, M., Larsen, P.K., Jensen, L.Aa. (2012): Ultra-low energy buildings for storage in museums and archives. *Healthy Buildings 2012*, 8-12 July, Brisbane, 6 pp (Electronic). *(With peer review)*

Ryhl-Svendsen, M., Johnsen, J.S., Jensen, L.Aa. (in press, 2013): A new climate control strategy for the National Museum of Denmark. *Climate for Collections: Standards and Uncertainties*, Doerner Institute, 7-9 November 2012, Munich.

Ryhl-Svendsen, M., Jensen, L.Aa., Larsen, P.K., Bøhm, B., Padfield, T. (in press, 2013): A museum storage building controlled by solar energy. *Climate for Collections: Standards and Uncertainties*, Doerner Institute, 7-9 November 2012, Munich. *(With peer review)*

Larsen, P.K., Ryhl-Svendsen, M., Jensen, L.Aa., Padfield, T. (submitted abstract): Energy efficient museum stores and archives in Denmark - a review. *Heritage Science and Sustainable Development for the Preservation of Art and Cultural Assets – on the Way to the Green Museum*. International Workshop: April 11th – 12th, 2013, Rathgen Research Laboratorium, Berlin.

12.3 Report

Ryhl-Svendsen, M., Jensen, L.Aa., Bøhm, B., Larsen, P.K. (2010): *Fællesmagasinet i Vejle, Ribe Antikvarisk Samlings Magasin, Fællesmagasinet for Museer i Midt- og Østjylland. UMTS-projekt "Lav-energi klimakontrol af museumsmagasiner". Energi- og luftkvalitetsmålinger – statusrapport*. Projektnr. 952805, Nationalmuseet, Bevaringsafdelingen, Brede, 32 pp. [in Danish]

12.4 Other

Jensen, J. (2008): Kulturskatte i passivt indeklima. *HVAC Magasinet* 1 (January), pp. 22-24. [*Portrait of our research group]*

Data and observations from this research project provided the ground for the formulation of a new climate control strategy for storage areas at the National Museum of Denmark (*Klimakontrolstrategi for Nationalmuseets magasiner 2011-2013*. Internal strategy paper: J.nr. 2010-019304, Samlings- og Registreringsudvalget, Nationalmuseet).

12.5 Related work within the UMTS-funded project

Larsen, P.K. (2011): The moisture equilibrium in Kippinge Church, Denmark. *ICOM-CC 16th Triennial Conference*, Lisbon 19-23 September 2011, ICOM Committee for Conservation, 7 pp (CD-ROM). *(With peer review)*

Larsen, P.K. (2011): The hygrothermal performance in Hellerup church, Denmark. *Proceedings for the Nordic Symposium on Building Physics*, Tampere, Finland, 29 May – 2 June 2011, pp. 807-814. *(With peer review)*

Ryhl-Svendsen, M. (2009): Use of steady-state mass balances for modeling cultural heritage environments. *Eastern Analytical Symposium 2009: EAS Abstracts*, Somerset, New Jersey, p. 25.

Ryhl-Svendsen, M. (2010): The generation of indoor air pollution from surface reactions. *IAQ2010: 9th Indoor Air Quality Meeting*, 21-23 April 2010, Chalon-sur-Saône, p. 89.

Padfield, T., Jensen, L.Aa. (2011): Humidity buffering by absorbent materials. *Proceedings for the Nordic Symposium on Building Physics*, Tampere, Finland, 29 May – 2 June 2011, pp. 475-482. *(With peer review)*

Ryhl-Svendsen, M. (2011): Passive sorption of organic compounds on clay bricks. *INDOOR AIR 2011, The 12th International Conference on Indoor Air Quality and Climate*, June 5-11, Austin, Texas. International Society of Indoor Air Quality (ISIAQ) & The University of Texas at Austin, 2 pp. (CD-ROM). *(With peer review)*

Ryhl-Svendsen, M. (2011): The influence of urban air pollution in archives. *ICOM-CC 16th Triennial Conference*, Lisbon 19-23 September 2011, ICOM Committee for Conservation, 7 pp (CD-ROM). *(With peer review)*

12.6 Related work outside the UMTS-funded project

Larsen, P.K., Broström, T. (2011): Climate control in historic buildings in Denmark. *World Renewable Energy Congress 2011*, 8-13 May 2011, Linköping, Sweden, 8 pp. *(With peer review)*

Padfield, T., Larsen, P.K. (2004): Designing museums with a naturally stable climate. *Studies in Conservation* 49, pp. 131-137.

Padfield, T., Larsen, P.K. (2005): Low-energy air conditioning of archives. *ICOM-CC 11th Triennial Conference*, The Hauge, 12-16 September 2005, ICOM Committee for Conservation, pp. 677–680. *(With peer review)*

Reilly, J.M., Johnsen, J.S., and Jensen. L. Aa., (2007): Documenting and optimizing storage conditions at the National Museum of Denmark. *Museum Microclimates*, 19-23 November 2007, National Museum of Denmark, Copenhagen , pp. 123-128. *(With peer review)*

Ryhl-Svendsen, M., Clausen, G. (2009): The effect of ventilation, filtration and passive sorption on indoor air quality in museum storage rooms. *Studies in Conservation* 54, pp. 35-48. *(With peer review)*

13. Additional literature

Some of the storage facilities have been the subject for investigation by other research groups.

Main publications include:

13.1 Joint Storage Facility in Vejle

Christensen, J.E., Janssen, H., Tognolo, B. (2010): *Passive hygrothermal control of a museum storage building in Vejle*. DTU Civil Engineering-Report-R-220 (UK), April 2010, Department of Civil Engineering, Technical University of Denmark, 35 pp.

Christensen, J.E., Janssen, H., Tognolo, B. (2010): Hygrothermal performance optimization of a museum storage building. *Thermal Performance of the Exterior Envelopes of Whole Buildings*, XI International Conference, December 5-9, 2010, Clearwater Beach, Florida, 10 pp.

Janssen, H., Christensen, J.E. (2013): Hygrothermal optimisation of museum storage spaces. *Energy and Buildings* 56, pp. 169-178.

Knudsen, L.R., Rasmussen, M.H. (2005): Building a new shared storage facility for 16 museums and archives. *ICOM-CC 11th Triennial Conference*, The Hauge, 12-16 September 2005, ICOM Committee for Conservation, pp. 648-654.

13.2 Royal Library

Vest, M., Kejser, U.B., Bruun, C. (2008): New long-term storage facilities at the Royal Library, Denmark: storage requirements for mixed collections. *ICOM-CC 15th Triennial Conference*, New Delhi, 22-26 September 2008, ICOM Committee for Conservation, pp. 808-814.
[*mainly on Stack 2; an extension to Stack 1 described in this report*]

Appendix

Reports on air exchange rate measurements by the PFT-method,
Danish Building Research Institute (SBi), Aalborg University [in Danish]:

I)

Notat: Nationalmuseet, ventilationsmålinger v. hj. a. PFT-metoden i fire magasinbygninger.
Niels Christian Bergsøe, Energi & Miljø, SBi, 10. marts 2011, Journal nr. 732-082.

II)

Notat: Nationalmuseet, ventilationsmålinger, Arnamagnæanske Samling, KUA.
Niels Christian Bergsøe, Energi & Miljø, SBi, 16. august 2011, Journal nr. 732-082.

Report on

air exchange rate

measurements:

Ørholm

Vejle

Ribe

Randers

Basic and dry climate

storage rooms

Notat

Statens Byggeforskningsinstitut
AALBORG UNIVERSITET

Nationalmuseet, ventilationsmålinger v. hj. a. PFT-metoden i fire magasinbygninger

Energi & Miljø
Niels Christian Bergsøe

10. marts 2011
Journal nr. 732-082

Nationalmuseet har med assistance fra SBi gennemført målinger af den gennemsnitlige ventilation i fire magasinbygninger – Magasinhal P i Ørholm, Fællesmagasinet i Vejle, Magasinet i Ribe og Fællesmagasinet i Randers. I hver af magasinbygningerne er der gennemført to målinger. I Magasinhal P i Ørholm er der yderligere gennemført en pilotmåling. Målingerne er gennemført ved hjælp af den såkaldte PFT-metode.

PFT-metoden (PFT = **P**er**F**luorcarbon **T**racer) er en passiv multi-sporgasmetode efter konstant-dosering princippet. Sporgas frigives kontinuert, med en kendt rate og passivt fra nogle små sporgaskilder. Registrering af den gennemsnitlige sporgaskoncentration i rumluften sker ved passiv opsamling i adsorptionsrør.

En sporgaskilde består af et lille metalhylster, som er lukket i den ene ende med en silikoneprop, hvorigennem sporgassen diffunderer. Et adsorptionsrør består af et glasrør, som indeholder en adsorbent beslægtet med aktivt kul. Adsorptionsrørene analyseres i laboratoriet ved termisk desorption og gaschromatografi.

Det er med PFT-metoden muligt at anvende flere forskellige sporgastyper samtidigt. En bygning eller en bolig kan derfor opdeles i zoner, så også interne luftudvekslinger mellem zonerne kan bestemmes.

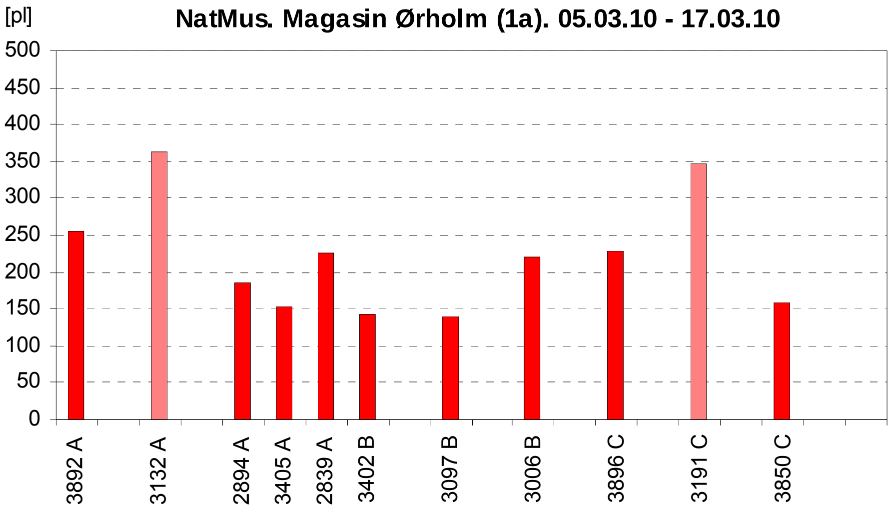
Målinger med PFT-metoden gennemføres over en periode, og resultatet af målingen er de gennemsnitlige ventilationsforhold i måleperioden. Afhængig af måleomstændighederne kan måleperiodens varighed være fra mindre end et døgn og op til flere uger eller måneder.

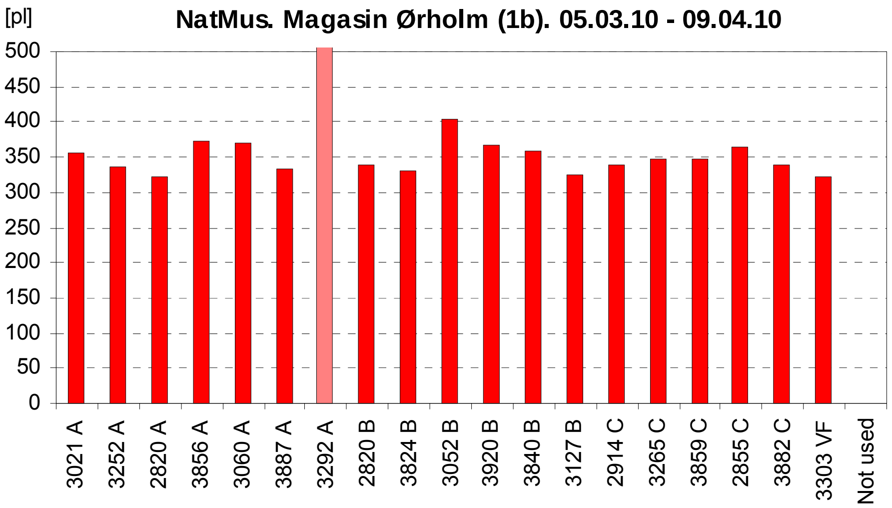
I tre af de fire magasinbygninger er målingerne gennemført som 2-zone målinger d. v. s. ved simultan anvendelse af to forskellige sporgastyper, mens én måling er gennemført som 1-zone måling. I alle fire tilfælde har måleperioden været ca. én måned.

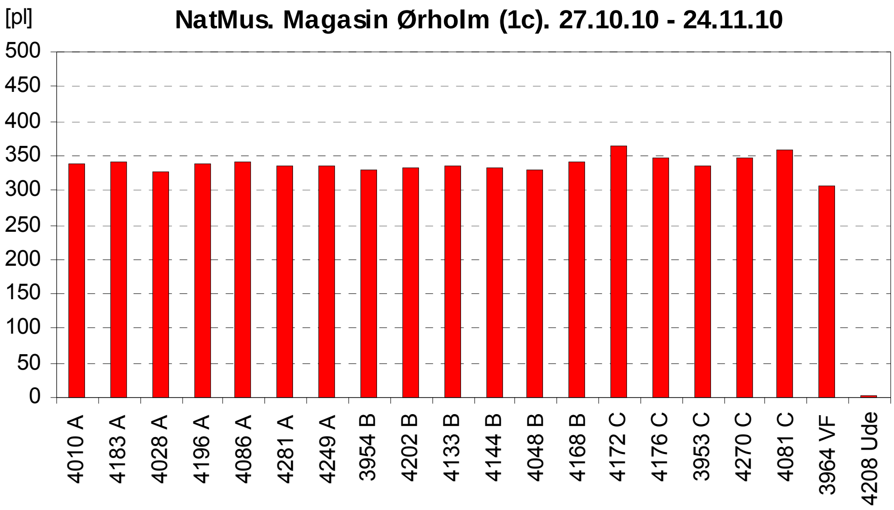
I Magasinhal P i Ørholm er der desuden gennemført en pilotmåling af ca. 2 ugers varighed og med et reduceret antal adsorptionsrør. Formålet var at verificere, at PFT-metoden ville være egnet til anvendelse ved de påtænkte målinger. Baggrunden for tvivlrådigheden var, at magasinbygningerne – i relation til PFT-metodens typiske anvendelse – udgør særdeles store voluminer og med lave indetemperaturer. Sporgaskildernes emissionsrate er temperaturafhængig med faldende rate ved faldende temperatur. På den baggrund måtte det forventes, at der ville forekomme lave sporgaskoncentrationer i magasinerne og dermed lavt sporgasindhold i adsorptionsrørene. I modsat retning taler forventeligt lave ventilationsrater og forholdsvis lange måleperioder for, at adsorptionsrørene ikke desto mindre alligevel måtte forventes at indeholde tilstrækkelige mængder sporgas til, at der kunne foretages pålidelige analyser. Resultatet af pilotmålingen var, at PFT-metoden er egnet til de anvendelse ved de påtænkte målinger.

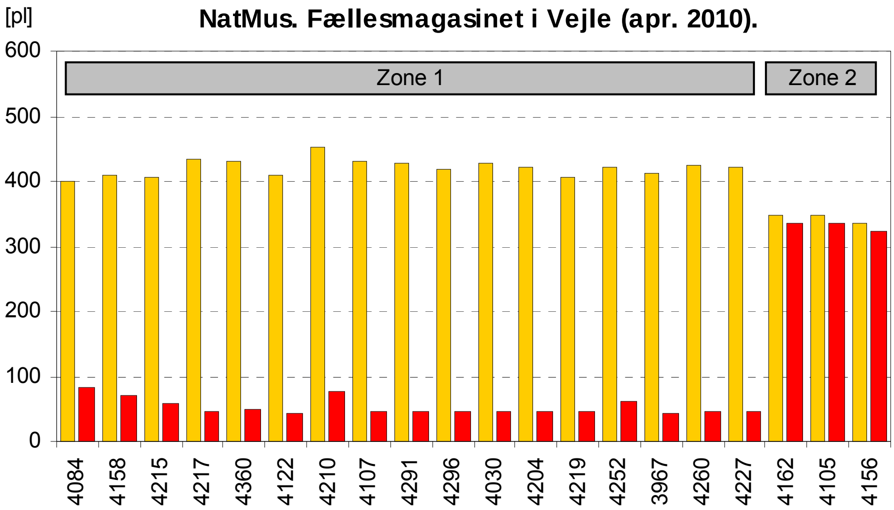
SBi har medvirket ved opsætning af udstyret i Magasinhal P i Ørholm ved pilotmålingen og ved den første egentlige måling, mens Nationalmuseet har stået for opsætning af udstyret ved den anden måling og ved begge målinger i de øvrige tre magasinbygninger. SBi har stået for klargøring af udstyret forud for målingerne og efterfølgende analyse af de eksponerede adsorptionsrør. Tabellen nedenfor sammenfatter resultaterne; på de næste sider følger PFT-resultatskemaer. Figurerne er taget med for at illustrere variationer i sporgasmængden i de anvendte adsorptionsrør.

	Magasin	Zone	Vol. [m3]	Temp. [°C]	Avg. ACH [h^{-1}]
	Magasinhal P, Ørholm				
1a	05.03.10 – 17.03.10 (pilot)	Hele Magasinhal P	11.000	9,5	0,05 ± 27 %
1b	05.03.10 – 09.04.10	Hele Magasinhal P	11.000	11,5	0,07 ± 16 %
1c	27.10.10 – 24.11.10	Hele Magasinhal P	11.000	11,5	0,06 ± 15 %
	Fællesmagasinet, Vejle				
2a	24.03.10 – 21.04.10	Gns. zone 1 og 2	19.438	9/10	0,04 ± 14 %
		1: Magasin A, C, D	17.057	9,0	0,04 ± 17 %
		2: Magasin B	2.381	10,0	0,01 ± 72 %
2b	25.10.10 – 22.11.10	Gns. zone 1 og 2	19.438	11/12	0,05 ± 15 %
		1: Magasin A, C, D	17.057	11,0	0,05 ± 17 %
		2: Magasin B	2.381	12,0	0,01 ± 60 %
	Magasin, Ribe				
3a	23.03.10 – 21.04.10	Gns. zone 1 og 2	6.501	16/10	0,03 ± 15 %
		1: Lille, tørt magasin	287	16,0	0,02 ± 95 %
		2: Stort basismagasin	6.214	10,0	0,03 ± 17 %
3b	23.03.10 – 21.04.10	1-z. analyse, PMCH	6.501	10,3	0,03 ± 16 %
3c	26.10.10 – 26.11.10	2-z. analyse ej mulig; defekt PMCP kilde	-	-	-
3d	26.10.10 – 26.11.10	1-z. analyse, PMCH	6.501	13,1	0,03 ± 19 %
	Fællesmagasinet, Randers				
4a	25.03.10 – 23.04.10	Gns. zone 1 og 2	13.364	10/9	0,03 ± 11 %
		1: Lille, tørt magasin	2.080	10,0	0,06 ± 18 %
		2: Stort basismagasin	11.284	9,0	0,03 ± 16 %
4b	25.10.10 – 23.11.10	Gns. zone 1 og 2	13.364	13/12	0,04 ± 10 %
		1: Lille, tørt magasin	2.080	13,0	0,08 ± 18 %
		2: Stort basismagasin	11.284	12,0	0,03 ± 15 %


[pl]
NatMus. Magasin Ørholm (1a). 05.03.10 - 17.03.10
500
450
400
350
300
250
200
150
100
50
0
3892 A
3132 A
2894 A
3405 A
2839 A
3402 B
3097 B
3006 B
3896 C
3191 C
3850 C


[pl]
NatMus. Magasin Ørholm (1b). 05.03.10 - 09.04.10
500
450
400
350
300
250
200
150
100
50
0
3021 A
3252 A
2820 A
3856 A
3060 A
3887 A
3292 A
2820 B
3824 B
3052 B
3920 B
3840 B
3127 B
2914 C
3265 C
3859 C
2855 C
3882 C
3303 VF
Not used


[pl]
NatMus. Magasin Ørholm (1c). 27.10.10 - 24.11.10
500
450
400
350
300
250
200
150
100
50
0
4010 A
4183 A
4028 A
4196 A
4086 A
4281 A
4249 A
3954 B
4202 B
4133 B
4144 B
4048 B
4168 B
4172 C
4176 C
3953 C
4270 C
4081 C
3964 VF
4208 Ude


[pl]
NatMus. Fællesmagasinet i Vejle (apr. 2010).
600
500
400
300
200
100
0
Zone 1
Zone 2
4084
4158
4215
4217
4360
4122
4210
4107
4291
4296
4030
4204
4219
4252
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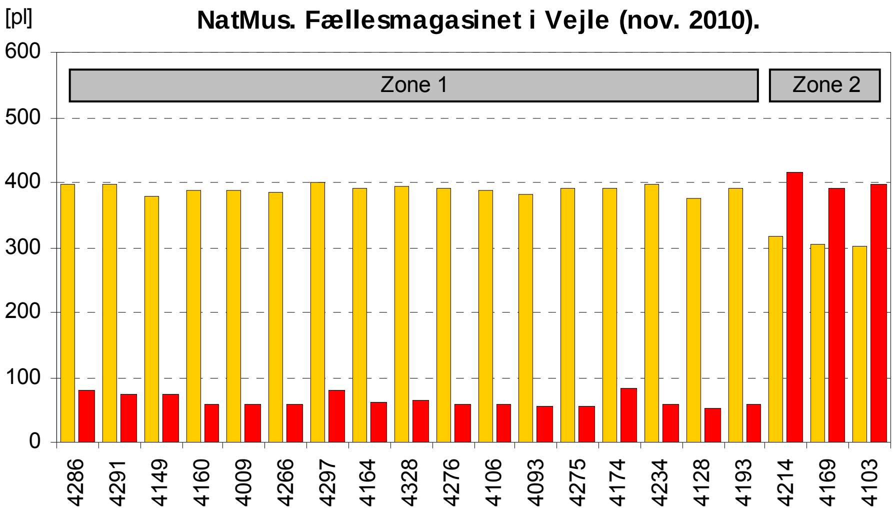
4227
4162
4105
4156


[pl]
NatMus. Fællesmagasinet i Vejle (nov. 2010).
600
500
400
300
200
100
0
Zone 1
Zone 2
4286
4291
4149
4160
4009
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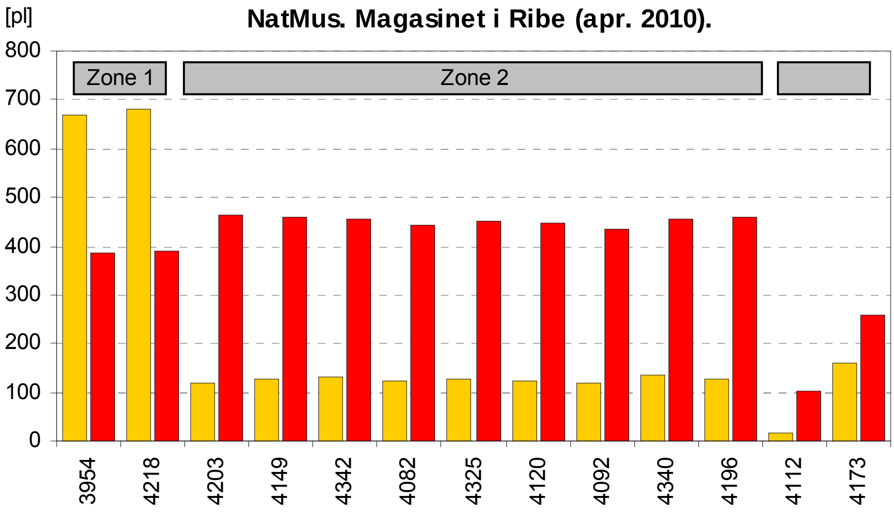
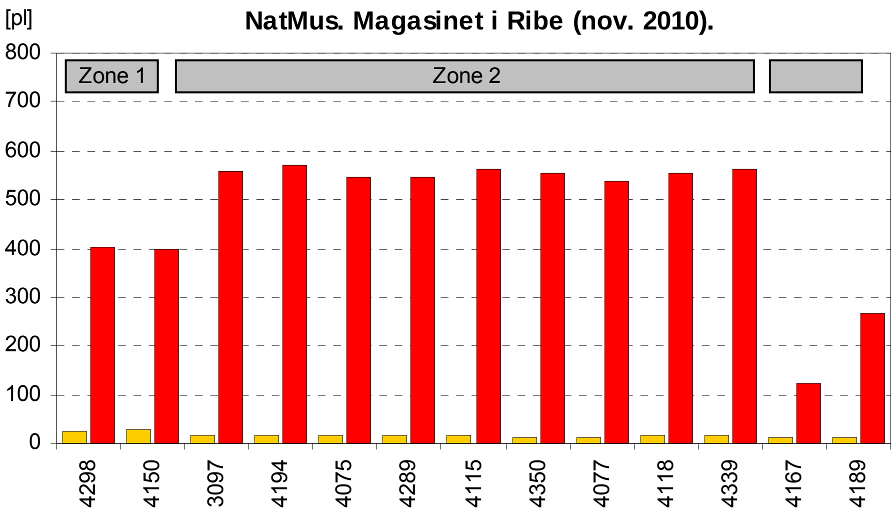
4193
4214
4169
4103

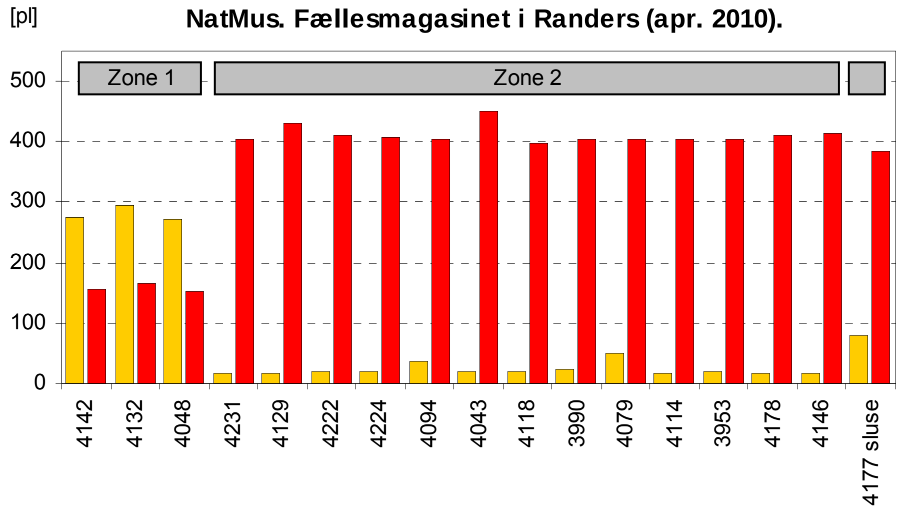


Rørene 4112 og 4173 indgår ikke i målingen; anbragt i henholdsvis depot-rum og modtagelse - indgang til magasin.

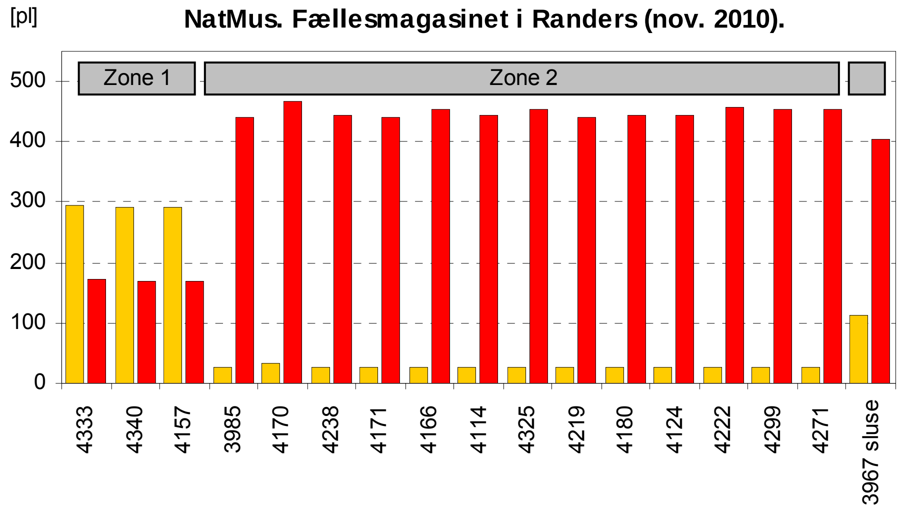


Rørene 4167 og 4189 indgår ikke i målingen; anbragt i henholdsvis depot-rum og modtagelse - indgang til magasin.

Bemærk: Defekt PMCP (gul) sporgaskilde; 2-zone analyse af målingen er desværre ikke mulig.



Rør 4177 indgår ikke i målingen; anbragt i indgangssluse til magasiner.



Rør 3967 indgår ikke i målingen; anbragt i indgangssluse til magasiner.

PFT-measurement

v. 44

Building	: NatMus. Magasin Ørholm (1)		Date:	17.12.2010
Project	: 732-082		Enclosure:	1a
Measurement Start:	05.03.10 at 10:30	Duration: 291,8 hours		
Measurement End :	17.03.10 at 14:15		Analysis:	19.03.2010

Results

Total infiltration rate:	513,4 m^3/h	(138,3)	[27%]
Total air change rate:	0,05 h^{-1}	(0,01)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	513,4	138,3	[27]	513,4	138,3	[27]	513,4	138,3	[27]
2									
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2			
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1			
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]	
Zone		PMCH	SD%
1	Hele magasinet	18,5	[23]
2	Not defined		
3	Not defined		

		Zone and emitter data					
		Volume	Type	Number	Ref. rate	Temp.	Est. rate
Zone		[m^3]			[nl/h]	[°C]	[nl/h]
1	Hele magasinet	11000,0	PMCH	12	19860	9,5	9509
2	Not defined						
3	Not defined						

Rackfactor(s):	PMCH: 0,238	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,25
		Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,27
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,00
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1		Zone 2	Zone 3	Excluded samplers			
	Sampler	PMCH	Sampler	Sampler	Sampler	PMCP	PMCH	PDCH
1	3892	255,9			3132	231,7	363,6	0,0
2	2894	185,2			3191	201,0	345,7	0,0
3	3405	152,4						
4	2839	225,3						
5	3402	143,6						
6	3097	140,2						
7	3006	220,1						
8	3896	229,8						
9	3850	159,1						

PFT-measurement

v. 44

Building	: NatMus. Magasin Ørholm (2)	Date:	17.12.2010
Project	: 732-082	Enclosure:	1b
Measurement Start:	05.03.10 at 10:30	Duration: 838,5 hours	
Measurement End :	09.04.10 at 09:00	Analysis:	15.04.2010

Results

Total infiltration rate: 740,3 m^3/h (114,9) [16%]
Total air change rate: 0,07 h^{-1} (0,01)

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	740,3	114,9	[16]	740,3	114,9	[16]	740,3	114,9	[16]
2									
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2			
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1			
3 → 2			
3 → 1			

Analysis

Average Zone Concentration [pl/l]

Zone		PMCH	SD%
1	Hele magasinet	14,2	[6]
2	Not defined		
3	Not defined		

Zone and emitter data

Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Hele magasinet	11000,0	PMCH	12	19860	11,5	10504
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,286

Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,12
Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,16
Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,00
Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1 Sampler	Zone 1 PMCH	Zone 2 Sampler	Zone 3 Sampler	Excluded samplers Sampler	PMCP	PMCH	PDCH
1	3021	355,6			3292	291,8	507,5	0,0
2	3252	335,7						
3	2860	322,8						
4	3856	373,6						
5	3060	369,3						
6	3887	333,8						
7	2820	340,0						
8	3823	330,4						
9	3052	402,7						
10	3920	367,4						
11	3840	359,6						
12	3127	325,5						
13	2914	338,6						
14	3265	346,5						
15	3859	346,2						
16	2855	363,0						
17	3882	338,9						
18	3303	321,5						

PFT-measurement

v. 48

Building	: NatMus. Magasin Ørholm (Nov. 2010)	Date:	17.12.2010
Project	: 732-082	Enclosure:	1c
Measurement Start:	27.10.10 at 10:00	Duration: 671,0 hours	
Measurement End :	24.11.10 at 09:00	Analysis:	02.12.2010

Results

Total infiltration rate: 620,3 m^3/h (93,9) [15%]
Total air change rate: 0,06 h^{-1} (0,01)
Outdoor air supply: - l/s pr. m^2 (Gross floor area: 0 m^2)

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	620,3	93,9	[15]	620,3	93,9	[15]	620,3	93,9	[15]
2									
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2			
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1			
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]	
Zone		PMCH	SD%
1	Hele magasinet	16,9	[3]
2	Not defined		
3	Not defined		

		Zone and emitter data					
		Volume	Type	Number	Ref. rate	Temp.	Est. rate
Zone		[m^3]			[nl/h]	[°C]	[nl/h]
1	Hele magasinet	11000,0	PMCH	12	19860	11,5	10504
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,282

Uncertainty GC: 10 %
Uncertainty mixing: 5 %
Uncertainty samplers: 2 %
Uncertainty emitters: 10 %

Uncertainty concentration matrix: 0,11
Uncertainty air flow matrix: 0,15
Condition number of conc. matrix: 1,00

Samplers

Measured Volume [pl]

	Zone 1		Zone 2	Zone 3	Excluded samplers			
	Sampler	PMCH	Sampler	Sampler	Sampler	PMCP	PMCH	PDCH
1	4010	338,1			4208	5,7	3,9	0,0
2	4183	340,2						
3	4028	325,7						
4	4196	338,3						
5	4086	340,4						
6	4281	335,2						
7	4249	335,6						
8	3954	330,3						
9	4202	333,1						
10	4133	336,3						
11	4144	331,5						
12	4048	330,6						
13	4168	340,4						
14	4172	363,3						

Fortsættes

Samplers

Measured Volume [pl]

	Zone 1		Zone 2	Zone 3	Excluded samplers			
	Sampler	PMCH	Sampler	Sampler	Sampler	PMCP	PMCH	PDCH
15	4176	346,8						
16	3953	334,8						
17	4270	346,4						
18	4081	357,2						
19	3964	307,7						

v. 45

PFT-measurement

Building	: NatMus. Fællesmagasinet i Vejle (apr. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	2a
Measurement Start:	24.03.10 at 13:30	Duration: 668,5 hours	
Measurement End :	21.04.10 at 10:00	Analysis:	23.04.2010

Results

Total infiltration rate:	737,1 m^3/h	(105,7)	[14%]
Total air change rate:	0,04 h^{-1}	(0,01)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	707,7	117,5	[17]	712,6	129,6	[18]	844,1	144,4	[17]
2	29,3	21,0	[72]	24,5	43,0	[176]	160,8	27,5	[17]
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2	131,4	33,0	[25]
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1	136,3	49,7	[36]
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]			
Zone		PMCP	SD%	PMCH	SD%
1	Magasin A, C, D	28,7	[3]	1,9	[24]
2	Magasin B	23,5	[2]	11,6	[2]
3	Not defined				

		Zone and emitter data					
Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Magasin A, C, D	17057,0	PMCP	15	45045	9,0	21033
2	Magasin B	2381,0	PMCH	2	3310	10,0	1625
3	Not defined						

Rackfactor(s):	PMCP: 0,407	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,197	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,17
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,51
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	4084	399,0	83,5	4162	347,4	334,3					
2	4158	408,7	72,0	4105	348,8	335,6					
3	4215	407,5	58,5	4156	335,2	322,9					
4	4217	433,2	46,7								
5	4360	429,4	50,1								
6	4122	407,7	44,6								
7	4210	451,4	76,9								
8	4107	429,8	45,6								
9	4291	429,2	45,8								
10	4296	417,9	45,3								
11	4030	428,8	46,5								
12	4204	421,2	47,4								
13	4219	407,1	45,0								
14	4252	420,0	62,8								

fortsættes

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
15	3967	412,3	43,9								
16	4260	424,6	47,2								
17	4227	420,1	46,9								

PFT-measurement

v. 48

Building	: NatMus. Fællesmagasinet i Vejle (nov. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	2b
Measurement Start:	25.10.10 at 13:30	Duration: 667,5 hours	
Measurement End :	22.11.10 at 09:00	Analysis:	01.12.2010

Results

Total infiltration rate: 930,3 m³/h (138,3) [15%]
Total air change rate: 0,05 h^{-1} (0,01)
Outdoor air supply: - l/s pr. m² (Gross floor area: 0 m²)

	Infiltration			Exfiltration			Total		
Zone	[m³/h]	SD	SD%	[m³/h]	SD	SD%	[m³/h]	SD	SD%
1	899,9	148,6	[17]	958,9	166,8	[17]	1071,9	179,9	[17]
2	30,4	18,1	[60]	-28,6	44,5	[-156]	143,4	24,1	[17]
3									

	Interzone				Interzone		
Zone	[m³/h]	SD	SD%	Zone	[m³/h]	SD	SD%
1 → 2	112,9	28,0	[25]	2 → 1	172,0	51,4	[30]
2 → 3				3 → 2			
1 → 3				3 → 1			

Analysis

Average Zone Concentration [pl/l]

Zone		PMCP	SD%	PMCH	SD%
1	Magasin A, C, D	24,8	[2]	2,3	[16]
2	Magasin B	19,6	[3]	14,3	[3]
3	Not defined				

Zone and emitter data

Zone		Volume [m³]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Magasin A, C, D	17057,0	PMCP	15	45045	11,0	23242
2	Magasin B	2381,0	PMCH	2	3310	12,0	1794
3	Not defined						

Rackfactor(s):	PMCP: 0,379	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,200	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,17
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,48
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	4286	396,8	79,7	4214	316,1	416,0					
2	4291	398,3	73,9	4169	303,1	390,1					
3	4149	378,0	72,6	4103	301,9	395,4					
4	4160	387,2	59,2								
5	4009	388,6	59,3								
6	4266	384,6	57,8								
7	4297	401,3	81,2								
8	4164	392,1	61,6								
9	4328	392,9	63,8								
10	4276	392,2	58,2								
11	4106	389,2	58,0								
12	4093	381,4	55,8								
13	4275	389,8	56,7								
14	4174	390,0	84,4								

Fortsættes

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
15	4234	396,4	57,3								
16	4128	376,6	53,4								
17	4193	391,2	59,6								

PFT-measurement

v. 45

Building	: NatMus. Magasinet i Ribe (apr. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	3a-2z
Measurement Start:	23.03.10 at 12:30	Duration: 692,5 hours	
Measurement End :	21.04.10 at 09:00	Analysis:	23.04.2010

Results

Total infiltration rate:	163,9 m^3/h	(24,3)	[15%]
Total air change rate:	0,03 h^{-1}	(0,00)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	4,8	4,5	[95]	-3,0	7,7	[-258]	33,4	5,7	[17]
2	159,1	27,0	[17]	166,9	30,2	[18]	195,5	33,7	[17]
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2	36,4	9,3	[26]
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1	28,6	7,3	[26]
3 → 2			
3 → 1			

Analysis

Average Zone Concentration [pl/l]

Zone		PMCP	SD%	PMCH	SD%
1	Lille, tørt magasin	70,5	[1]	21,2	[0]
2	Stort basismagasin	13,1	[5]	24,7	[2]
3	Not defined				

Zone and emitter data

Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Lille, tørt magasin	287,0	PMCP	1	3003	16,0	1977
2	Stort basismagasin	6214,0	PMCH	5	8275	10,0	4062
3	Not defined						

Rackfactor(s):	PMCP: 0,646	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,317	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,17
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,59
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	3954	668,2	387,1	4203	120,6	463,0		4112	16,0	103,9	0,0
2	4218	679,9	388,3	4149	125,1	461,3		4173	158,1	258,3	0,0
3				4342	131,9	457,1					
4				4082	122,4	444,7					
5				4325	125,5	450,7					
6				4120	121,8	446,6					
7				4092	117,1	434,9					
8				4340	134,6	454,0					
9				4196	129,2	458,8					

PFT-measurement

v. 45

Building	: NatMus. Magasinet i Ribe (apr. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	3b-1z
Measurement Start:	23.03.10 at 12:30	Duration: 692,5 hours	
Measurement End :	21.04.10 at 09:00	Analysis:	23.04.2010

Results

Total infiltration rate:	173,4 m^3/h	(27,0)	[16%]
Total air change rate:	0,03 h^{-1}	(0,00)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	173,4	27,0	[16]	173,4	27,0	[16]	173,4	27,0	[16]
2									
3									

Interzone				Interzone			
Zone	[m^3/h]	SD	SD%	Zone	[m^3/h]	SD	SD%
1 → 2				2 → 1			
2 → 3				3 → 2			
1 → 3				3 → 1			

Analysis

		Average Zone Concentration [pl/l]	
Zone		PMCH	SD%
1	Lille, tørt mag. + stort mag.	23,8	[6]
2	Not defined		
3	Not defined		

		Zone and emitter data					
Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Lille, tørt mag. + stort mag.	6501,0	PMCH	5	8275	10,3	4124
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,313

Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,12
Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,16
Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,00
Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1		Zone 2	Zone 3	Excluded samplers			
	Sampler	PMCH	Sampler	Sampler	Sampler	PMCP	PMCH	PDCH
1	3954	387,1			4112	16,0	103,9	0,0
2	4218	388,3			4173	158,1	258,3	0,0
3	4203	463,0						
4	4149	461,3						
5	4342	457,1						
6	4082	444,7						
7	4325	450,7						
8	4120	446,6						
9	4092	434,9						
10	4340	454,0						
11	4196	458,8						

PFT-measurement

v. 48

Building	: NatMus. Magasinet i Ribe (nov. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	3c-2z
Measurement Start:	26.10.10 at 10:00	Duration: 742,5 hours	
Measurement End :	26.11.10 at 08:30	Analysis:	01.12.2010

Results

Total infiltration rate: 4010,5 m^3/h (1.563,0) [39%]
Total air change rate: 0,62 h^{-1} (0,24)
Outdoor air supply: - l/s pr. m^2 (Gross floor area: 0 m^2)

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	3902,7	1587,6	[41]	13946,4	4211,9	[30]	14105,8	4267,3	[30]
2	107,8	29,8	[28]	-9936,0	3974,1	[-40]	267,1	74,8	[28]
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2	159,3	65,9	[41]
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1	10203,1	4036,0	[40]
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]			
Zone		PMCP	SD%	PMCH	SD%
1	Lille, tørt magasin	0,2	[9]	22,4	[0]
2	Stort basismagasin	0,1	[9]	31,0	[2]
3	Not defined				

		Zone and emitter data					
		Volume	Type	Number	Ref. rate	Temp.	Est. rate
Zone		[m^3]			[nl/h]	[°C]	[nl/h]
1	Lille, tørt magasin	287,0	PMCP	1	3003	16,0	1977
2	Stort basismagasin	6214,0	PMCH	5	8275	13,0	4712
3	Not defined						

Rackfactor(s):	PMCP: 0,063	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,348	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,34
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	2,53
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	4298	24,3	402,2	3097	15,3	555,9		4167	10,3	122,0	0,0
2	4150	27,5	399,8	4194	16,4	568,6		4189	11,2	267,4	0,0
3				4075	15,2	547,0					
4				4289	14,5	546,0					
5				4115	16,8	561,3					
6				4350	14,3	555,9					
7				4077	13,6	539,2					
8				4118	14,9	555,2					
9				4339	18,1	560,4					

PFT-measurement

v. 48

Building	: NatMus. Magasinet i Ribe (nov. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	3d-1z
Measurement Start:	26.10.10 at 10:00	Duration: 742,5 hours	
Measurement End :	26.11.10 at 08:30	Analysis:	01.12.2010

Results

Total infiltration rate:	165,0 m^3/h	(30,6)	[19%]
Total air change rate:	0,03 h^{-1}	(0,00)	
Outdoor air supply:	- l/s pr. m^2	(Gross floor area: 0 m^2)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	165,0	30,6	[19]	165,0	30,6	[19]	165,0	30,6	[19]
2									
3									

	Interzone				Interzone		
Zone	[m^3/h]	SD	SD%	Zone	[m^3/h]	SD	SD%
1 → 2				2 → 1			
2 → 3				3 → 2			
1 → 3				3 → 1			

Analysis

Average Zone Concentration [pl/l]

Zone		PMCH	SD%
1	Lille, tørt mag. + stort mag.	28,7	[12]
2	Not defined		
3	Not defined		

Zone and emitter data

Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Lille, tørt mag. + stort mag.	6501,0	PMCH	5	8275	13,1	4735
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,339	Uncertainty GC: 10 %	Uncertainty concentration matrix:	0,16
	Uncertainty mixing: 5 %	Uncertainty air flow matrix:	0,19
	Uncertainty samplers: 2 %	Condition number of conc. matrix:	1,00
	Uncertainty emitters: 10 %		

Samplers

Measured Volume [pl]

	Zone 1 Sampler	PMCH	Zone 2 Sampler	Zone 3 Sampler	Excluded samplers Sampler	PMCP	PMCH	PDCH
1	4298	402,2			4167	10,3	122,0	0,0
2	4150	399,8			4189	11,2	267,4	0,0
3	3097	555,9						
4	4194	568,6						
5	4075	547,0						
6	4289	546,0						
7	4115	561,3						
8	4350	555,9						
9	4077	539,2						
10	4118	555,2						
11	4339	560,4						

PFT-measurement

v. 45

Building	: NatMus. Fællesmag. i Randers (apr. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	4a
Measurement Start:	25.03.10 at 14:00	Duration: 622,0 hours	
Measurement End :	20.04.10 at 12:00	Analysis:	23.04.2010

Results

Total infiltration rate:	431,2 m^3/h	(45,6)	[11%]
Total air change rate:	0,03 h^{-1}	(0,00)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	126,4	23,0	[18]	179,6	31,1	[17]	206,1	31,9	[15]
2	304,8	47,6	[16]	251,5	46,6	[19]	331,2	51,3	[15]
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2	26,4	13,2	[50]
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1	79,7	18,1	[23]
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]			
Zone		PMCP	SD%	PMCH	SD%
1	Lille tørt magasin	14,8	[4]	9,3	[4]
2	Stort basismagasin	1,2	[44]	24,1	[4]
3	Not defined				

		Zone and emitter data					
		Volume	Type	Number	Ref. rate	Temp.	Est. rate
Zone		[m^3]			[nl/h]	[°C]	[nl/h]
1	Lille tørt magasin	2080,0	PMCP	2	6006	10,0	2949
2	Stort basismagasin	11284,0	PMCH	10	16550	9,0	7728
3	Not defined						

Rackfactor(s):	PMCP: 0,292	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,305	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,15
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,11
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	4142	275,2	156,3	4231	17,4	405,4		1177 sluse	79,0	383,9	0,0
2	4132	294,6	166,8	4129	16,6	430,4					
3	4048	271,5	153,8	4222	19,8	409,9					
4				4224	19,5	407,9					
5				4094	35,0	404,1					
6				4043	19,5	451,0					
7				4118	18,4	398,7					
8				3990	22,6	404,0					
9				4079	50,6	402,8					
10				4114	17,0	403,6					
11				3953	20,3	402,6					
12				4178	17,1	409,6					
13				4146	17,3	415,6					

PFT-measurement

v. 48

Building	: NatMus. Fællesmag. i Randers (nov. 2010).	Date:	17.12.2010
Project	: 732-082	Enclosure:	4b
Measurement Start:	25.10.10 at 10:00	Duration: 709,0 hours	
Measurement End :	23.11.10 at 23:00	Analysis:	01.12.2010

Results

Total infiltration rate: 509,9 m³/h (53,0) [10%]
Total air change rate: 0,04 h^{-1} (0,00)
Outdoor air supply: - l/s pr. m^2 (Gross floor area: 0 m^2)

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	156,4	28,2	[18]	216,7	36,4	[17]	252,7	39,1	[15]
2	353,5	54,8	[15]	293,2	54,7	[19]	389,5	60,2	[15]
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2	36,0	8,6	[24]
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1	96,3	21,9	[23]
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]			
Zone		PMCP	SD%	PMCH	SD%
1	Lille tørt magasin	14,0	[0]	9,1	[1]
2	Stort basismagasin	1,3	[8]	23,9	[2]
3	Not defined				

		Zone and emitter data					
Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Lille tørt magasin	2080,0	PMCP	2	6006	13,0	3420
2	Stort basismagasin	11284,0	PMCH	10	16550	12,0	8972
3	Not defined						

Rackfactor(s):	PMCP: 0,303	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	PMCH: 0,316	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,15
		Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,11
		Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1			Zone 2			Zone 3	Excluded samplers			
	Sampler	PMCP	PMCH	Sampler	PMCP	PMCH	Sampler	Sampler	PMCP	PMCH	PDCH
1	4333	293,7	172,8	3985	26,9	441,3		3967	113,2	402,8	0,0
2	4340	292,6	169,6	4170	34,4	467,1					
3	4157	291,6	170,4	4238	25,8	442,4					
4				4171	25,5	439,7					
5				4166	27,5	452,3					
6				4114	26,0	442,8					
7				4325	26,6	453,8					
8				4219	26,1	439,4					
9				4180	26,3	445,2					
10				4124	26,5	442,8					
11				4222	27,3	457,3					
12				4299	27,0	455,2					
13				4271	26,2	452,9					

Report on

air exchange rate

measurements:

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AALBORG UNIVERSITET

Nationalmuseet, ventilationsmålinger, Arnamagnæanske Samling, KUA

Energi & Miljø
Niels Christian Bergsøe

16. august 2011
Journal nr. 732-082

Nationalmuseet har med assistance fra SBi gennemført to målinger af ventilationen i en arkivboks ved Den Arnamagnæanske Samling, KUA. Målingerne er gennemført ved hjælp af den såkaldte PFT-metode.

PFT-metoden

PFT-metoden (PFT = **P**er**F**luorcarbon **T**racer) er en passiv multi-sporgas-metode efter konstant-dosering princippet. Sporgas frigives kontinuert, med en kendt rate og passivt fra nogle små sporgaskilder. Registrering af den gennemsnitlige sporgaskoncentration i rumluften sker ved passiv opsamling i adsorptionsrør.

En sporgaskilde består af et lille metalhylster, som er lukket i den ene ende med en silikoneprop, hvorigennem sporgassen diffunderer. Et adsorptionsrør består af et glasrør, som indeholder en adsorbent beslægtet med aktivt kul. Adsorptionsrørene analyseres i laboratoriet ved termisk desorption og gaschromatografi.

Det er med PFT-metoden muligt at anvende flere forskellige sporgastyper samtidigt. En bygning eller en bolig kan derfor opdeles i zoner, så også interne luftudvekslinger mellem zonerne kan bestemmes.

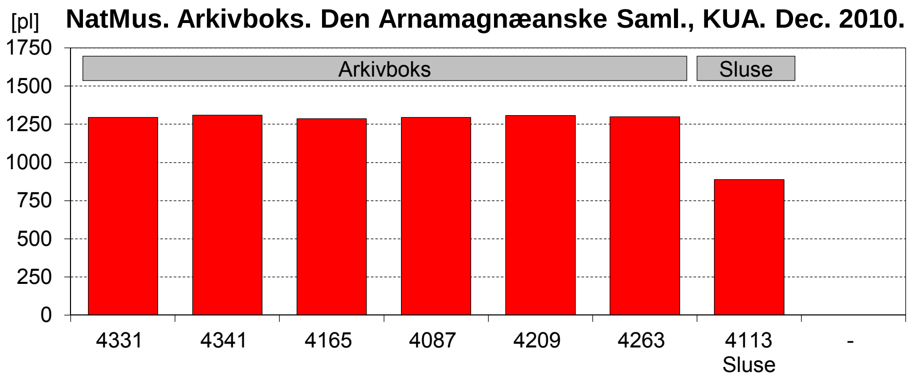
Målinger med PFT-metoden gennemføres over en periode, og resultatet af målingen er de gennemsnitlige ventilationsforhold i måleperioden. Afhængig af måleomstændighederne kan måleperiodens varighed være fra mindre end et døgn og op til flere uger eller måneder.

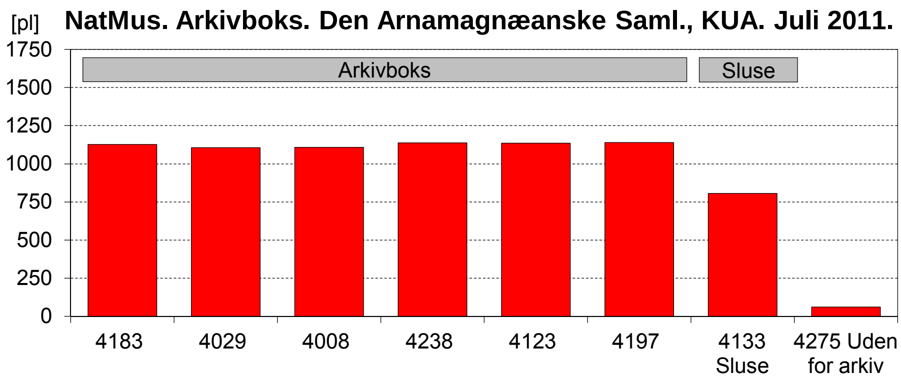
Målingerne

Nationalmuseet har ved begge målinger stået for opsætning og nedtagning af udstyret, mens SBi har stået for udlån og klargøring af udstyret forud for målingerne samt efterfølgende gaschromatografisk analyse af de eksponerede adsorptionsrør.

Den første måling er gennemført i en periode i opvarmningssæsonen nemlig fra den 3. til den 20. december 2010. Den anden måling er gennemført i en sommerperiode; fra den 27. juni til den 13. juli 2011.

Figurerne på næste side viser sporgasindholdet i de enkelt adsorptionsrør, mens de efterfølgende skemaer viser resultaterne af målingerne. Adsorptionsrørene har ved de to målinger været anbragt på samme måde og i de samme positioner. Såvel i figurerne som i skemaerne er adsorptionsrørene arrangeret herefter.





Ved målingen i december 2010 er den samlede infiltration til arkivet målt til 4,8 m^3/h, som svarer til et luftskifte på 0,04 h^{-1}.

Ved målingen i juli 2011 er den samlede infiltration målt til 7,7 m^3/h svarende til et luftskifte på 0,06 h^{-1}.

PFT-measurement

v. 48

Building	: NatMus. Den Arnamagnæanske Saml., KUA.	Date:	15.08.2011
Project	: 732-082 (december 2010)	Enclosure:	1
Measurement Start:	03.12.10 at 12:00	Duration: 405,0 hours	
Measurement End :	20.12.10 at 09:00	Analysis:	21.12.2010

Results

Total infiltration rate: 4,8 m^3/h (0,7) [15%]
Total air change rate: 0,04 h^{-1} (0,01)
Outdoor air supply: 0,03 l/s pr. m^2 (Gross floor area: 40 m^2)

	Infiltration			**Exfiltration**			**Total**		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	4,8	0,7	[15]	4,8	0,7	[15]	4,8	0,7	[15]
2									
3									

	Interzone		
Zone	[m^3/h]	SD	SD%
1 → 2			
2 → 3			
1 → 3			

	Interzone		
Zone	[m^3/h]	SD	SD%
2 → 1			
3 → 2			
3 → 1			

Analysis

		Average Zone Concentration [pl/l]	
Zone		PMCH	SD%
1	Arkivboks, KUA	211,7	[1]
2	Not defined		
3	Not defined		

		Zone and emitter data					
		Volume	Type	Number	Ref. rate	Temp.	Est. rate
Zone		[m^3]			[nl/h]	[°C]	[nl/h]
1	Arkivboks, KUA	120,0	PMCH	1	1655	14,5	1014
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,553	Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
	Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,15
	Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,00
	Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1		Zone 2	Zone 3	Excluded samplers			
	Sampler	PMCH	Sampler	Sampler	Sampler	PMCP	PMCH	PDCH
1	4331	1294			4113	26,5	888,2	0,0
2	4341	1310			-	0,0	0,0	0,0
3	4165	1286						
4	4087	1295						
5	4209	1307						
6	4263	1299						

v. 48

PFT-measurement

Building	: NatMus. Den Arnamagnæanske Saml., KUA.	Date:	15.08.2011
Project	: 732-082 (juli 2011)	Enclosure:	2
Measurement Start:	27.06.11 at 11:00	Duration: 382,5 hours	
Measurement End :	13.07.11 at 09:30	Analysis:	20.07.2011

Results

Total infiltration rate:	7,7 m^3/h	(1,2)	[15%]
Total air change rate:	0,06 h^{-1}	(0,01)	
Outdoor air supply:	0,05 l/s pr. m^2	(Gross floor area: 40 m^2)	

	Infiltration			Exfiltration			Total		
Zone	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%	[m^3/h]	SD	SD%
1	7,7	1,2	[15]	7,7	1,2	[15]	7,7	1,2	[15]
2									
3									

Interzone			
Zone	[m^3/h]	SD	SD%
1 → 2			
2 → 3			
1 → 3			

Interzone			
Zone	[m^3/h]	SD	SD%
2 → 1			
3 → 2			
3 → 1			

Analysis

Average Zone Concentration [pl/l]

Zone		PMCH	SD%
1	Arkivboks, KUA	182,4	[1]
2	Not defined		
3	Not defined		

Zone and emitter data

Zone		Volume [m^3]	Type	Number	Ref. rate [nl/h]	Temp. [°C]	Est. rate [nl/h]
1	Arkivboks, KUA	120,0	PMCH	1	1655	21,5	1411
2	Not defined						
3	Not defined						

Rackfactor(s): PMCH: 0,519

Uncertainty GC:	10 %	Uncertainty concentration matrix:	0,11
Uncertainty mixing:	5 %	Uncertainty air flow matrix:	0,15
Uncertainty samplers:	2 %	Condition number of conc. matrix:	1,00
Uncertainty emitters:	10 %		

Samplers

Measured Volume [pl]

	Zone 1 Sampler	Zone 1 PMCH	Zone 2 Sampler	Zone 3 Sampler	Excluded samplers Sampler	PMCP	PMCH	PDCH
1	4183	1127			4133	27,8	806,0	0,0
2	4029	1106			4275	12,0	61,4	0,0
3	4008	1108						
4	4238	1137						
5	4123	1136						
6	4197	1141						

Low-energy Museum Storage Buildings: Climate, Energy Consumption, and Air Quality.
UMTS Research Project 2007-2011: Final Data Report

Project no. 10821521

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