CONDENSATION INVESTIGATION

AT THE NATIONAL GALLERY OF AUSTRALIA OFF-SITE FACILITY

Ariel Lizcano Ortega

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Department of Mechanical Engineering

Macquarie University

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Supervisor: Dr Nazmul Huda

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STATEMENT OF CANDIDATE

I, Ariel Lizcano Ortega, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment at any academic institution.

Student's Name: Ariel Lizcano Ortega

Student's Signature:

Date: 07/11/2016

ABSTRACT

Condensation is an issue that has been affecting The Australian National Gallery of Art off-site facility - Hume storage warehouse for more than 20 years. A condensation investigation aims to detect the causes and provide recommendations to this problem considering aspects and properties such as heating and cooling conditions, temperature, moisture content, ventilation and structural construction. It has been found that air infiltration and thermal bridging are characteristics that have a great impact in the generation of surface condensation within the facilities. An engineering approach to the conditions and remedies related to specific sites of condensation are analysed and thermal modelled using Ansys and heat3 software. This thesis pursuits the stability of the conditioned space in order to preserve the contents and collections which possess a high social and economic value for Australia's art.

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Chapter 1

Introduction

The National Gallery of Australia (NGA) is an iconic building located in the city of Canberra, which was opened by her majesty Queen Elizabeth II in 1982 and is part of the Commonwealth of Australia's National cultural institution for the visual arts [1]. The storage of the national's collections and valuable items for cultural display is located at the NGA off-site facility at Hume Canberra where the environmental conditions of the space have been adapted for preservation and conservation.

The NGA off-site storage facility - Hume was built in the early 90s with an approximated area of 5602 m^2. Moisture condensation is an issue that has had a negative effect since the first years of operation. Some temporary remedies and upgrades have been ongoing over the years that have tried to completely eliminate the condensation in the building without definite success. The following investigation aims to identify the causes of condensation in the building and recommend a possible solution.

The following document provides an overview of materials used for its construction such as the structural frame, walls, roofs, ceiling, floors and insulation to study their thermal conductivity properties (R- value, U-value) and how their layout is related to the environmental conditions of Canberra. In addition, how the Heating Ventilation and Air Conditioning System (HVAC) operates in order to maintain the required internal conditions such as temperature and humidity will also be looked at.

Air quality is an important factor to avoid condensation; therefore, its behaviour and properties such as the airborne movement, vapour pressure and diffusion are of interest. Monitoring of the right conditions within the space reduces the germination of microbiological threats like mould, mildew, fungus and insect proliferation that can not only affect the health of people but the deterioration of paintings, fabrics, canvas and varnish layers. Control of temperature, relative humidity and dust is critical in the preservation, and any constant fluctuation of these parameters not only may affect archival collections such as books, papers, and photographs, but may also cause structural damage such as decay, corrosion, cracks and infiltration or exfiltration of the air in the building itself [2][3][4][5]. The infiltration and exfiltration of air through a building enclosure can be a major source of energy loss and creates potential for moisture damage due to condensation as well [6].

Adequate climate control in a space requires the selection and installation of the right equipment to comply with specifications. Some of the equipment can be complex, but it is critical to identify their capabilities for an optimal performance. Some of the most common elements in an Air Handling Unit are humidifiers, dehumidifiers, heating and cooling coils and filters.

The prediction of how a building is going to perform under certain parameters is of interest in many industries. The use of thermal analysis software such as Ansys and Heat3 is of great usefulness to determine heat transfer characteristics at specific sections within the facility and it is an important tool to pursue the main objective of this project.

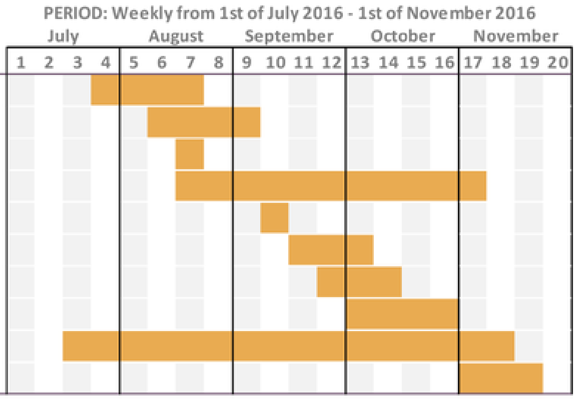
Figure 1.1. NGA off-site facility location.

1.1 Project goal

Steensen Varming Ltd. It is a consulting engineering company that has been appointed to investigate the causes of condensation that are currently affecting the National Gallery of Australia Off-site facility in order to identify and recommend the most appropriate solutions to be implemented. As part of the company, I was appointed to carry out the investigation and provide documentation based on observation, inspection, measurements, calculations, analysis and modelling resulting in an optimal engineering application to this project.

1.2 Project Plan

ACTIVITY	ACTUAL START (Weeks)	ACTUAL DURATION (Weeks)
Research on Condensation	4	4
Review of related doc.	6	4
On site inspection	7	1
Project Development	7	11
Measurements	10	1
Calculations and Analysis	11	3
Ansys & Heat3 Training	12	3
Modelling	13	4
Meeting with Supervisors	3	16
Final Delivery of the Project	17	3



1.3 Project Scope

Condensation is a factor that affects most buildings and causes deterioration in infrastructure, decay in materials, microbiological growth and risk to valuable contents. To carry out this investigation, it has been necessary to review documentation and data from the time the building was built. Based on the information supplied by the National Gallery of Australia Department of Services and their personnel, an engineering approach has been put into plan. The required visits to understand the configuration of the building and close observation has led to the utilization of a thermal analysis software to predict and detect the source or sources of condensation that are affecting the installations. By doing so, a more complete diagnostic based on measurements, analysis of energy and heat, building services characteristics and modelling can be combined in order to recommend a suitable solution.

Chapter 2

Background and related Work

2.1. Moisture

Moisture is a factor that affects buildings and there is a need to control such a parameter in order to avoid negative effects in the structure and its components. It is well known in the building industry that water in any of its states may cause deterioration and damage over time. Sources of moisture such as those released by human action, generated by environmental effects (rain and snow) and exerted from the ground have been identified as external parameters of humidity that are likely to affect internal relative humidity [7].

The penetration of water within a building must be avoided by using impervious materials over the exterior of a building creating a complete sealed isolation layer. The reduction of this characteristic is observed in buildings through time resulting in roof leaks, infiltration of rainwater and accumulation of moisture within cracks and crawl spaces. Movement of moisture through materials can occur in different transfer mechanisms such as transfer through suction, molecular liquid/vapour diffusion, capillary flow, evaporation, condensation, diffusion through the pores of the material, hygroscopicity, movement due to gravity and sorption [8][9].

Moisture is everywhere in the form of water vapour and it is basically humidity in the air that circulates all around in the atmosphere. The movement of water vapour in the air and into indoor spaces is caused by the lightness of its molecules in comparison to the nitrogen and oxygen molecules and this increases buoyancy and decreases density in the moist air. Therefore, the difference of vapour pressure between indoors and outdoors has to be considered to understand the behaviour of the building envelope [10]. In order to control moisture in the desired space, it is necessary to identify environmental and structural parameters.

2.1.1 Relative Humidity (RH)

This characteristic is measured as a percentage of the amount of water that can be contained in the air and it is subjected to the variation of temperature and moisture content. Relative humidity is a parameter present in the design conditions in a space and can be calculated based on the pressure generated by the molecules of vapour that are present in the air.

$$(\%)\ RH = \frac{Actual\ Vapour\ Pressure}{Saturation\ Vapour\ Pressure\ at\ air\ temperature} * 100 \qquad (1)$$

The percentage of saturation depends on the mass of moisture rather than the vapour pressure providing similar information than relative humidity [11].

$$\%\ Saturation = \frac{Mass\ of\ moisture\ in\ the\ air}{Mass\ of\ moisture\ required\ to\ saturate\ air\ at\ a\ temperature} * 100 \qquad (2)$$

Any change in temperature affects relative humidity and any fluctuation based on internal and external conditions needs to be controlled by balancing the moisture generated and the moisture removed [10] [12].

2.1.2 Mould Growth

Excess moisture can generate condensation which is a suitable condition for mould to grow. The air in the atmosphere contains oxygen which is essential for mould spores to germinate under the right temperatures; therefore, the time that moisture is present in a surface dictates the rate of proliferation. During winter, external surfaces are colder than internal surfaces in a building, and the internal surface is colder than the air at the centre of the room. This condition creates a difference in relative humidity of approximately 10% in the interior surface, and if the room relative humidity reaches 70% and is maintained like that for a long period of time, it creates optimal conditions for mould growth. The presence of water is not a requirement for mould to grow, but if the temperature of the surface is steady between 4°C and 40°C and the relative humidity of the surface increases over 70%, mould can germinate and grow while condensation does not occur until the relative humidity is 100% [13].

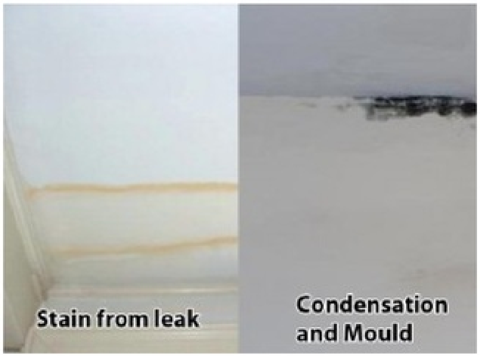


Figure 2.1. Example of deterioration of materials by leakage and condensation [14].

The temperature of the air in a room and relative humidity can be maintained at a desired level, but these conditions most probably do not reach every part of the building surfaces and its contents during winter. This creates potential mould growth in cavities and roof spaces. In summer, the same principle applies, and it is necessary to take into account that the mixed air in the air conditioned system is dehumidified below 70% relative humidity to avoid mould growth.

2.2 Building Materials

The variety of materials in a building makes it a complex structure with different types of properties and consequently different behaviours which may determine the relation to moisture content. The deterioration of materials in most cases depends on their moisture content and capability to absorb water. The kinetics of moisture transfer is a microstructural characteristic based on porosity. The structure, shape, size, distribution and networking are very difficult to define, and in many models, the pore structure correlated to moisture transport coefficients are based on empirical correction factors validated for a specific group of materials [16].

2.2.1 Insulation

The main factor for using insulation is to reduce the thermal heat loss or gain in a building and the energy consumption of cooling and heating systems. There are different types of insulation materials such as polyester, natural wool, glass wool, Rockwool, cellulose fibre, polystyrene, etc. and most of them aim to reduce thermal conductivity between the environmental exterior conditions and the desired internal conditions. The two most common types of insulation used are bulk insulation which has millions of small still air pockets and reflective foil insulation which reduces the radiant heat transfer across the enclosed space. The R value defines the thermal conductivity (resistance) of a material and ideally is manufactured to reduce moisture content from infiltrated capillary action. Nowadays, insulation is designed to reduce moisture transmission by incorporating vapour barriers to resist vapour diffusion and interstitial condensation. Plastics and foils are preferred for this, but technically they still have a degree of permeability. If the insulation is not manufactured or installed properly, moisture laden air will penetrate until the dew point is reached at which point condensation will take place [16]. The R value in Australia depends on the climate zone, type and height of the building and must comply with the Building Code of Australia (BCA).

Condensation control in roofs and void ceiling areas demand the use of vapour Permeable Underlays (VPU) to protect these areas from condensation. The main characteristic is their breathability allowing water vapour generated in the building to pass freely through and to prevent moisture from outside entering the void ceiling space if the roof is not ventilated [17].

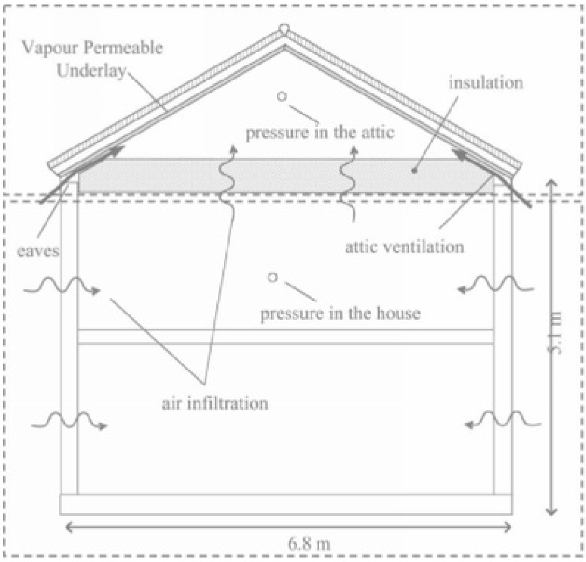


Figure 2.2. Cross section of a two-storey building with a cold pitch roof [17]

Insulation in general must comply under the Australian Building Codes Board, section J, to satisfy the performance requirements for thermal construction. Section J1.3 provides an overview of these requirements for roofs and ceilings.

Climate zone	**1, 2, 3, 4 and 5**	**6**	**7**	**8**
Direction of heat flow	Downwards		Upwards	
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of not more than 0.4	3.2	3.2	3.7	4.8
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of more than 0.4 but not more than 0.6	3.7	3.2	3.7	4.8
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of more than 0.6	4.2	3.2	3.7	4.8

Table 2.1. Roofs and ceilings- minimum R-value for each climate zone [18]

2.2.2 Thermal-conductivity

Heat transfer is the science that seeks to predict the energy transfer that may take place between material bodies as a result of temperature difference. The science of heat transfer seeks not merely to explain how heat energy may be transferred, but also to predict the rate at which the exchange will take place under certain specified conditions. In the presence of a multilayer wall or ceiling construction, the temperature gradient in each material varies, and the heat flow is determined by using the following equation [19].

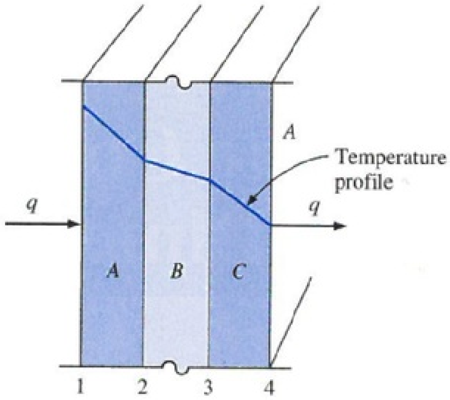


Figure 2.3. Heat transfer through a wall in one dimension [19].

$$q = \frac{Thermal\ Potential\ Difference}{Thremal\ Resistance} = \frac{T_1 - T_4}{\frac{\Delta x_A}{k_A}A + \frac{\Delta x_B}{k_B}A + \frac{\Delta x_C}{k_C}A} \quad (3)$$

Where,

q: $Heat\ flow\ (W)$

T_x: $Temperature$ (°C)

Δx: $Thicness\ of\ the\ layer\ (m)$

k_x: $Thermal\ conductivity\ \left(\frac{W}{m°C}\right)$

$A: Surface\ area\ (m^2)$

2.2.3 Sol Air Temperature

Sol air temperature is necessary to calculate a more accurate heat transfer rate at the outer surface of a wall or roof. This temperature takes into account the heat absorbed by radiation on the surface of the material at a determined time of the day and allows to have a more precise value of thermal-conductivity. The following equations describe the rate of heat entry and the solar air temperature [20].

$$Q' = h_{so}(T_{eo} - T_{so}) \quad (4)$$

$$T_{eo} = T_o + \frac{\alpha * (I_d + I_s)}{h_{so}} \quad (5)$$

Where,

Q': $Rate\ of\ heat\ entry\ into\ the\ outer\ surface\ \left(\frac{W}{m^2}\right)$

h_{so}: $Outside\ surface\ heat\ transfer\ coefficient\ \left(\frac{W}{m^2K}\right)$

T_{eo}: $Sol\ air\ temperature\ (°C)$

T_{so}: $Outside\ surface\ temperature\ (°C)$

α: $Absortion\ Coefficient$

I_d: $Direct\ solar\ radiation\ normal\ to\ surface\ \left(\frac{W}{m^2}\right)$

I_s: $Intensity\ of\ diffuse\ (sky)\ radiation\ normally\ incident\ on\ a\ surface\ \left(\frac{W}{m^2}\right)$

2.2.4 Climate zone

The climate zone is a standard classification that represents the experienced and expected type of weather conditions according to a geographic location. In Australia, there are eight climate zones and many regional sub-zones and each has distinctly different design and construction requirements [21]. The climate zones are differentiated on average temperature, humidity, wind patterns, precipitation rate and altitude above sea level.

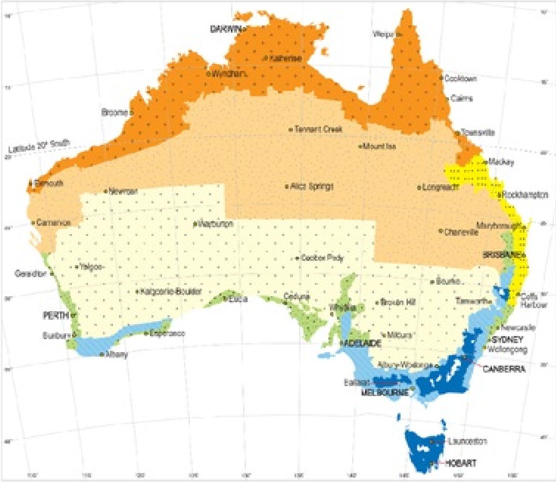


Figure 2.4. Climate zone map of Australia [21].

Zone	Description
1	Hot humid summer, warm winter
2	Warm humid summer, mild winter
3	Hot dry summer, warm winter
4	Hot dry summer, cool winter
5	Warm temperate
6	Mild temperate
7	Cool temperate
8	Alpine

Figure 2.5. Zone weather description [21].

2.3 Temperature

Temperature is a factor that influences condensation on a surface when it falls below the dew point temperature of the conditioned air. To prevent condensation without air conditioning, it is necessary to increase the temperature of the air in locations where condensation may have or had occurred [22]. One partial solution is the use of low speed and high volume industrial fans to raise the temperature of the air and proportionally increase its capacity of moisture per kilogram of dry air to reduce the relative humidity.

The relationship between the inner surface temperature and the dew point in a structure gives a good prediction of condensation and can be determined by using the following equations:

$$T_i \leq T_d$$

$$\Delta T = T_i \leq T_d \leq 0 \qquad (6)$$

where, ΔT stands for the difference between the inner surface temperature (T_i) and the air dew point temperature near the envelope (T_d) [23].

In a roof, the temperature can vary as much as 20 °C during the night of a clear sky day in cold seasons, and this phenomenon is based on the exchange of infrared radiation which might decrease the risk of condensation [15].

2.4 HVAC systems

The main characteristic of a Heating Ventilation and Air Conditioning system (HVAC) is to provide thermal comfort by supply fresh air quality into a space with the appropriate temperature and humidity. The HVAC system works by removing heat from the cooling space during hot days and supplying it during the colder days. In addition, it has control over certain parameters in the occupied zone by avoiding drafts, large air temperature gradients and large radiant asymmetry [24]. The comfort levels for humans lies in a humidity range between 40% and 60%, and for this reason it is necessary in most occasions to humidify or dehumidify the space. Also, the temperature of the indoor conditions must satisfy predetermined values between 21°C to 23°C for comfort level within the indoor space.

During colder days, the warm humid air in the interior space comes into contact with elements of the building structure that have been exposed to the exterior environmental cold conditions bringing the temperature down on the internal surface of the structure. This contact of warm air with the colder surface produces condensation on the surface if the humidification process is not controlled properly as the internal air may increase the dew point.

2.4.1 Forced Ventilation

The use of forced ventilation is a requirement in most buildings under many standards because it is more reliable than using natural ventilation and provides flexibility controlling the air intake and recirculated air to be supplied into the space. In addition, forced ventilation helps to extract air from areas where the production of moisture is high such as in bathrooms and kitchens. The use of fans is of great importance to extract the high moisture air but at the same time has to be controlled to avoid the extraction of useable air. Air exhausted that does not need to be replaced will increase the overall energy consumption within the system. When there is air movement with high moisture content produced from adjacent areas of the building, care should be taken to ensure that these rooms are not significantly cooler than the rest of the building as this could increase the risk of condensation in these areas [13].

To solve these issues and others, the use of Building Management systems (BMS) has been incorporated in the overall system. The BMS is a central programmable system that interacts with a series of sensors positioned within the space such as thermocouples, humidity sensors and pressure sensors. Also, the BMS has the ability to control components of the HVAC system such as fans, variable speed differentials (VSD), volumetric Air Valves (VAV), dampers, humidifiers and much more.

2.4.2 Dehumidifiers and Humidifiers

Dehumidifiers are one of the most used components in a HVAC system to remove moisture from the incoming air flow that is distributed into the conditioned space. This means reducing the moisture content per kilogram of dry air. Dehumidifiers are in most cases located within the Air Handling Unit (AHU) in plant rooms. The temperature of the air is reduced until the temperature dew point is reached creating condensation. The air passes over a cooler coil containing water at a much lower temperature that is recirculated by the chiller operation system.

Humidifiers also make up part of the HVAC system, and their function is to condition the space that has insufficient moisture by adding this moisture mechanically in the form of steam, water droplets or water mist in the airstream. The heat transfer involved in this process is associated with the latent heat required and the additional mass transfer into the airstream [25].

2.4.3 Psychrometric Chart

The psychrometric chart allows information related to moisture in the air and thermal properties to be presented in a graphical form. The understanding of this chart helps to explain and predict air characteristics based on a range of properties that can avoid surface condensation. The scales on its different axis allow information about dry and wet bulb temperature, humidity ratio, enthalpy, dew point, relative humidity, moisture content and specific volume to be obtained. In addition, the psychrometric chart helps to calculate and analyse the energy transfer required for HVAC processes such as cooling, heating, humidifying and dehumidifying [26].

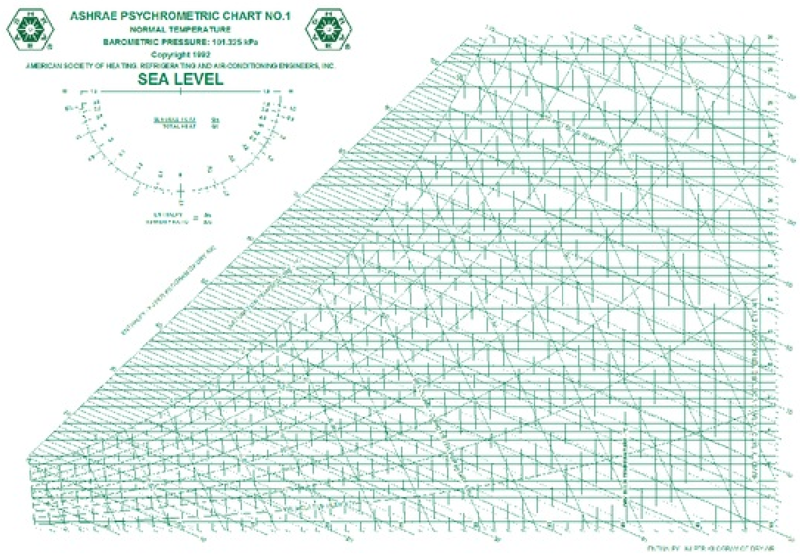


Figure 2.6 Psychrometric chart.

2.5 Condensation

In any building, condensation has been identified as one of the most severe problems and needs to be approached in the engineering process. Droplets of water especially during winter time have been found to commence with the deposition of warmer vapour atoms on a cool surface without the capability of retaining the same amount of water vapour. The vapour atoms evolve from nucleation and by releasing their excess of mass water, direct condensation is formed by coalescence until their size is large enough to slide off the surface [27] [28]. Air at any temperature is capable of containing a limited amount of moisture and this capability is directly proportional to the temperature. In addition, there is an increase in the vapour pressure exerted, so air containing a larger mass of water vapour has a higher vapour pressure than dryer air, which causes vapour to diffuse from high to low pressure areas [13].

At the same time that condensation occurs, there is an amount of heat that is generated in the process which is transferred to the surroundings on the surface reducing the probability of condensation [3]. However, anything that reduces the vapour pressure in the air or raises the temperature on the surface will reduce the presence of condensation [13] [29].

There are some guides that help to predict the amount of condensation in structures which are found in the BS5250 or CIBSE guides. The approach from several guides aims to determine factors such as: the type, amount and rate of heating in the building, the ventilation rate, the thermal properties of the materials and surfaces, the internal and external temperatures, the water vapour production within the space, the moisture content of the replacement outdoor air and the ability of the building contents to absorb and desorb water vapour [13]. Desorption is a reverse condensation phase which is another phenomenon that is essential in the understanding of condensation as the water vapour is released from the surface of a material by solar radiation creating a pressure difference that drives the water vapour inside the building [13].

By using the following equations, it is possible to estimate the amount of moisture that might be accumulated during a certain period. the temperature and vapour pressure at a particular layer of material in the composite structure.

$$m = \frac{\Delta P_v}{G} \quad (7)$$

$$T_n = T_{si} - \left[\frac{\left((T_{si} - T_{se}) * \sum_{si}^{n} R\right)}{\sum_{si}^{se} R}\right] \quad (8)$$

$$P_v = P_{vsi} - \left[\frac{\left((P_{vsi} - P_{vse}) * \sum_{si}^{n} G\right)}{\sum_{si}^{se} G}\right] \quad (9)$$

Where,

m: *Rate of vapour transfer per unit area* $\left(\frac{Kg}{m^2 s}\right)$

ΔP_v: *Vapour pressure difference across material or structure* (Pa)

G: *Vapour resistance of material or structure* $\left(\frac{N\ s}{Kg}\right)$

2.5.1 Thermal Bridging

It is common for buildings to have materials that present high thermal conductivity resulting in a decrease of insulation capabilities. For the construction and renovation of a building, it is necessary to consider the design barriers that are capable to isolate air, water and thermal infiltration and exfiltration. These parameters determine the energy used by the HVAC system, the durability of structural materials, internal contents and comfort. Any penetration of this protective thermal bridge layer can be classified as follows [30]:

Repeating Thermal Bridge: where bridges occur following a regular pattern and have significant heat loss affecting the overall heat transfer coefficient (U-value). This can be seen in timber joists, mortar joints, curtain walls and materials that cross from the exterior to the interior of the building.

Non repeating Thermal Bridges: where bridges occur by the joining of two materials or where the spacing in corners is too difficult for a complete seal. This can be seen where the insulation in the wall and floor do not join and in wall and roof junctions, lintels, and fittings [31].

The surface temperature factor (f) is an indicative factor to determine how well insulated a structure is. If the factor is close to 1, there is good insulation; however, if the factor is less than 0.5, there is a presence of a severe thermal bridge that needs to be addressed. Once the temperature factor has been calculated for a thermal bridge, it can be used to find the internal surface temperature for different internal and external temperature conditions. The surface temperature factor also aims to determine the internal surface relative humidity if the internal relative humidity is known [13].

$$f = \frac{T_{si} - T_o}{T_i - T_o} \quad (10)$$

Where,

$f: Surface\ Temperature\ Factor$

$T_{si}: Internal\ Surface\ Temperature$

$T_i: Internal\ Air\ Temperature$

$T_o: External\ AirTemperature$

The condensation in a surface can be also assessed by defining the condensation potential (CP) as the difference between the water vapor partial pressure in the air $P_v(air)$ and the water vapour saturation pressure on the surface $P_{sat}(surface)$, implying condensation for positive values [32]:

$$CP = P_v(air) - P_{sat}(surface) \quad (11)$$

The amount of risk condensation over time CPE can be estimated by multiplying the positive CP by the time it occurs [32].

$$\Delta T_{CP_{(>0)}}$$

$$CPE = CP_{(>0)} * \Delta T_{CP_{(>0)}} \quad (12)$$

2.6 Air infiltration

Air infiltration is a contributor to condensation and load increment on a building HVAC system if the air tightness enclosure is not effective [6]. The control of space air temperature and humidity when the building envelope is not properly sealed is challenging as condensation develops [33]. ISO 13789 refers to a steady calculation method to estimate the air infiltration losses for buildings without mechanical ventilation.

$$n_{inf} = n_{50} * e \quad (13)$$

Where, the air change via infiltration n_{inf} equals the air change at a difference pressure of 50 Pa (n_{50}) times the standard value coefficient (e) that is particular for every country [34].

By assuming a constant infiltration rate, the infiltration into the building depends on pressure differences over the building envelope. Where, Q is the air flow rate (m^3/s), C leakage coefficient (m^3/sPa^n), ΔP pressure difference and n is the flow exponent (none) [34].

$$Q = C * \Delta P^n \quad (14)$$

The stack effect on a building is another characteristic to take into account for analysis. The possible causes of air infiltration in a building might be related to the displacement of large volumes of unwanted air within the conditioned space. Stack effect is the consequence of differential temperature and pressure between the outside and inside air creating an imbalance of masses due to changes in density that is reflected on a vertical pressure gradient. In winter, the outside cold air gets into the building through openings; it warms up and becomes less dense, and by doing so it rises to the top of the building and leaves through any openings located in the ceiling or roof structure. The opposite effect takes place during summer days when the flow of outside hot air is reversed pushing out the cold air from the conditioned space. The pressure difference induced by the stack effect is described by the following equations [35]:

$$\Delta P_s = \rho g 273(Z_2 - Z_1)\left[\frac{1}{(T_{out} + 273)} - \frac{1}{(T_{in} + 273)}\right] \quad (15)$$

This equation can be summarised as follows:

$$\Delta P_s = -3455\ (Z_2 - Z_1)\left[\frac{1}{(T_{out} + 273)} - \frac{1}{(T_{in} + 273)}\right] \quad (16)$$

Where,

$\Delta P_s: Difference\ pressure\ caused\ by\ stack\ effect\ (Pa)$

$\rho: Air\ density\ at\ 0°C\ \left(\frac{Kg}{m^3}\right)$

$g: Acceleration\ due\ to\ gravity\ \left(\frac{m}{s^2}\right)$

$Z_1, Z_2: heights\ of\ the\ openings\ abobe\ ground\ (m)$

$T_{in}: Inside\ temperature\ (°C)$

$T_{out}: Outside\ temperature\ (°C)$

The wind effect is another characteristic that contributes to air infiltration in a building. In lower parts of the atmosphere, the wind presents a random pattern with alterations in velocity and direction that need to be averaged by meteorological stations. The data collected by these stations provides a statistical average over time. This information is utilised to have an approximation of the wind velocity at certain heights for building analysis. However, coefficient factors have been introduced for correction in the calculations which are based on the terrain conditions where the building is located. An approximated correction is suggested in BS 5952, 1991 and is presented in table 2.2 and reference the calculation of the wind speed at a particular height using the following equation [35].

$$v_z = v_m K z^a \qquad (17)$$

Terrain	*k*	*a*
Open, flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

Table 2.2. Terrain coefficients for wind speed (Source: BSI, 1991)[35].

In addition, the wind effect also contributes to a change in pressure on the different faces or façades of the building. This pressure distribution can be positive or negative and depends on the direction and velocity of the wind as shown in figure 2.7.

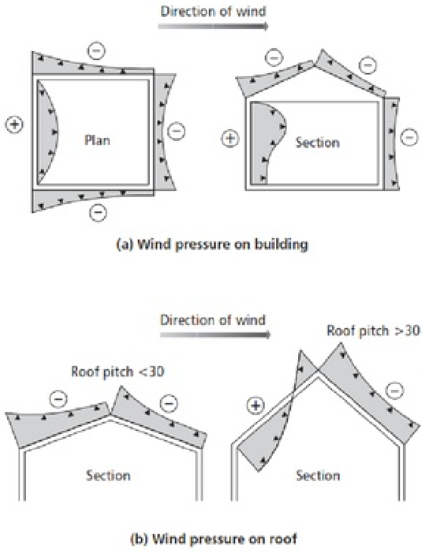


Figure 2.7. Wind pressure on different building surfaces [35].

The pressure in a pitched roof varies from negative to positive once the roof pitch is greater than 30°. In this calculation, a wind pressure coefficient is also introduced as a function of wind direction and spatial position on the building surface. However, this parameter needs tests using wind tunnels or Computational Fluid Dynamic analysis in order to have an accurate coefficient value [35]. Some typical coefficient values found in the literature are shown in table 2.3 and can be used in the following equation.

$$\Delta P_w = C_p * \frac{\rho}{2} * v^2 \quad (18)$$

Where,

$\Delta\rho_l$: *Density difference between outside air and inside air at the high of the leakage* $\left(\frac{Kg}{m^3}\right)$

ρ: *Air density* $\left(\frac{Kg}{m^3}\right)$

ΔP_w: *Difference pressure caused by wind* (Pa)

C_p: $Wind\ pressure\ coefficient\ dependent\ on\ building\ shape\ and\ wind\ shielding\ (-)$

v: $Wind\ velocity\ \left(\frac{m}{s}\right)$

Table 4.A1.2 Wind pressure coefficient data

Low–rise buildings (up to 3 storeys)

Length to width ratio: 1:1

Shielding condition: sheltered (i.e. surrounded by obstructions equivalent to half the height of the building)

Wind speed reference level: building height

Location		Wind angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.4	0.1	–0.3	–0.35	–0.2	–0.35	–0.3	0.1
Face 2		–0.2	–0.35	–0.3	0.1	0.4	0.1	–0.3	–0.35
Face 3		–0.3	0.1	0.4	0.1	–0.3	–0.35	–0.2	–0.35
Face 4		–0.3	–0.35	–0.2	–0.35	–0.3	0.1	0.4	0.1
Roof (> 10°)	Front	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
	Rear	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
	Average	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
Roof (11–30° pitch)	Front	–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
	Rear	–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
	Average	–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
Roof (>30° pitch)	Front	0.3	–0.5	–0.6	–0.5	–0.5	–0.5	–0.6	–0.5
	Rear	–0.5	–0.5	–0.6	–0.5	0.3	–0.5	–0.6	–0.5
	Average	–0.1	–0.5	–0.6	–0.5	–0.1	–0.5	–0.6	–0.5

Table 2.3. Wind pressure coefficient data [35].

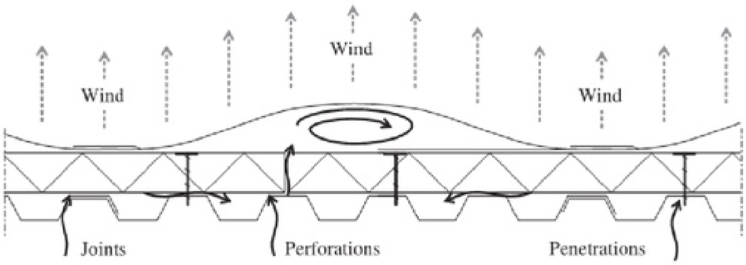


Figure 2.8. Wind forces inducing pressure differences on the outer roof membrane [15].

2.7 Pressurisation

This factor is strongly related to infiltration and exfiltration of air in the building construction and layout of materials. The objective is to prevent unwanted air transfer either way from the outside to the interior of the space or from the interior of the space to the exterior. The type of pressurisation is determined by the use of the space and can be positive pressurisation or negative pressurization. The direction always depends on the differential pressure going from the highest to the lowest pressure. In a common building envelope positive pressurization is applied to the space to compensate the volume of air that is lost between small structural clearance openings in doors, windows, fittings and those mentioned in the thermal bridging section. This particular factor is known as leakage and its relationship with the HVAC system may determine performance and the overall energy consumption of the system. For a space to have zero leakage it means that the space has been completely sealed. There are spaces that need strict control of air movement such as laboratories with high risk contaminants, isolation rooms with biological threat, etc. A zero leakage needs complete accuracy in the design and construction, however, it is extremely hard to achieve, so the use of negative pressure is necessary to guarantee control of the air stream. In order to provide a positive pressure in the space, the supply air must exceed the removed air from the space creating a surplus of air within the room and increasing the internal pressure in relation to adjacent spaces. If the adjacent space is the ambient condition, it must exceed the atmospheric pressure. In both cases, the air is pushed outwards. Negative pressure is the opposite, and the volume of supply air is less than the exhausted, creating a vacuum effect. The specific relationship between room differential pressure, room leakage area and the differential airflow (transfer airflow) is expressed by the following equation [35]:

$$Q = 840 * A * (\Delta P)^{\frac{1}{2}} \qquad (19)$$

Where,

$Q{:}\, Approximated\ flow\ rate\ through\ openings\ \left(\frac{L}{s}\right)$

$A{:}\, Total\ air\ leakage\ area\ \left(\frac{m^3}{h}\right)$

$\Delta P{:}\, differential\ pressure\ (Pa)$

2.8 Air Changes

Air changes are an important parameter to consider at the design stage of the HVAC system and must introduce not just the required air flow based in heat gain or loss within the space but the required ventilation that the space demands. An air change can be simply defined as the number of times that the total volume of air supplied by the HVAC to the space enters and leaves in a time period of one hour. The air changes equation is as follows:

$$AC = \frac{M\dot{V}}{\dot{V}_{space}} \qquad (20)$$

Where,

$AC: Air\ changes\ per\ hour$

$M\dot{V}: Approximated\ Make-up\ air\ volume\ required\ in\ the\ space\ \left(\frac{m^3}{h}\right)$

$\dot{V}: Volume\ of\ the\ space\ (m^3)$

The air changes required in the space is an empirical value that has been tabulated as an approximated value for different types of buildings and can be found in different building services guides such as those provided by ASHRAE, AIRAH, CIBSE, etc. These values can be different and are open to a wide range of interpretation. It is relevant to mention that these values do not take into account the specific type or location of leakages within the building but work as a reference to determine the amount of make-up air that needs to be supplied into the ventilation design.

Chapter 3

Experimental Procedures

The initial experimental procedure consisted on identifying the places where dripping water within the facilities has been described and discussions have been undertaken with personnel that are on-site on a regular basis to estimate frequency, particular times and days of occurrence. Inspection of the installations have been done to determine the state of the materials and surfaces and how they have been impacted due to condensation. Evaluation of the functioning of the Heating Ventilation and Air conditioning system was required in order to establish its design parameters and the relationship with the space design conditions. The Gathering of documentation was also required to determine the materials used for the construction of the storage facility although it was known that information might be outdated or incomplete because this is a building from the early 90's. A basic 3D Modelling of the building in Revit 2016 from floor plan drawings supplied by the department of services has been done to have a better understanding of the structural layouts. Revit is a Build Information Modelling (BIM) software that allows the assembly and virtual representation of different architectural, structural, services components and equipment such as those used in Mechanical, Electrical and Plumbing (MEP). Although the capabilities of this software are extensive and widely used in the building industry, for the purpose of this investigation, the model was just created for reference as the guidance material was not clear or supplied. Measurements of temperature and relative humidity within the facilities have been taken by using a humidity/temperature sensor device (Testo 625) with an operating temperature measurement range from -10 °C to 60 °C which possesses an accuracy of ±0.5 °C and a relative humidity operating range from 0% to 100% and an accuracy of 0.1%. In addition, surface temperatures were measured using an infrared thermometer Testo Quicktemp 860-T2 which has the capability to obtain readings over long distances.

Figure 3.1. Infrared thermometer Testo 860-T2 [36].

Figure 3.2. Testo 625 [36]

The investigation provides calculations of thermal resistivity and thermal transmittance to identify the compliance with regulations and standards. Modelling has been done using Ansys 17.2 student version to observe thermal characteristics of composite materials and to analyse the insulation capabilities. It is important to mention that Ansys student version has restrictions in a variety of parameters especially in the mesh generation which limited the refinement of the model analysis. The use of HEAT 3 software for steady heat transfer has been included in the modelling section to confirm and compare the results obtained by Ansys. The experimental procedure finishes by predicting the cause of condensation in the results and discussion section. Recommendations are provided in the conclusion section and are subjected to the National Gallery of Australia for implementation.

Chapter 4

Analysis and Results

4.1 Structural Analysis

From the documentation provided by the NGA off-site facility and inspection of the windowless building the structural materials used for its construction have been identified to be:

Structural steel columns

Concrete walls

Colorbond finish Zinc Steel roof decking (kilplok) with 50 mm steps at 3° pitch

Zinc Steel fascia to cover the steel channels in the rack beam between columns

Zinc steel box gutter

Figure 4.1. External façade of the NGA off-site facility.

The concept of "box in a box" is applied to provide an internal space adequate for the purpose of art conservation and storage. The materials used for this purpose are mentioned below:

Steel profile cladding

Foil backed fibreglass insulation blanket under the roof decking

Cool room panels - polystyrene insulation

Light gauge wire mesh over and in between purlin to keep insulation in place

Plasterboard suspended grid ceiling in the offices

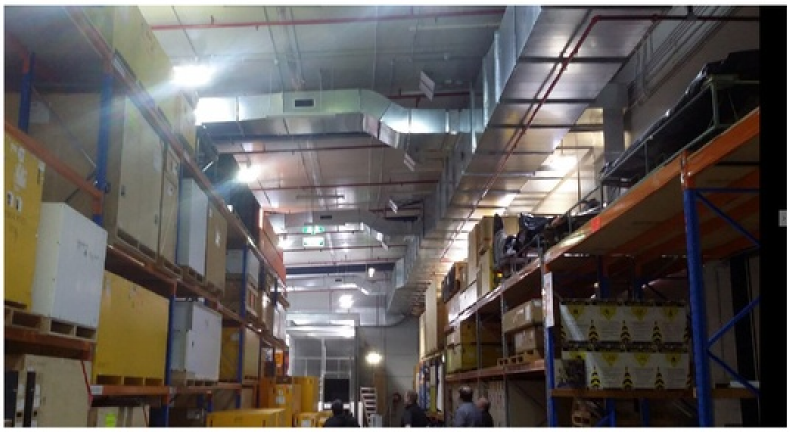


Figure 4.2. Internal overview of the NGA off-site facility.

The information collected for the analysis of materials has been provided by the department of services at the NGA and shows structural drawings and floor plan drawings which have been used for analysis and which are attached to appendices B and C.

4.2 Heating Ventilation and Air Conditioning (HVAC)

The HVAC system is currently being upgraded by Benmax Mechanical contractors, and there is an investigation into the condensation problem being conducted by Steensen Varming in order to improve the internal conditions and reduce the extremely high energy costs involved with the original HVAC system. As part of the upgrade within the installations, both companies inspected the building as well as the mechanical plant comparing the original and designed air flows and static pressures and provided a review on parameters such as temperature control, humidification control, air handling capacity, chiller capability, boiler capability, ductwork and supply-return air registers.

4.2.1 Design Conditions

Ambient design conditions

Summer: 34°C Dry Bulb, 21°C Wet Bulb

Winter: - 4°C Dry Bulb, - 4 Wet Bulb

Interior design conditions:

Temperature: 22°C ± 1.5°C

Relative Humidity (RH): 55% ± 5%

4.2.2 Plant and Building Analysis

The NGA off-site facility has been conditioned as three zones for air distribution, but the space itself has been divided into different sections to accommodate different types of art items and offices. In addition, the building has two floors for this purpose (ground floor and first floor). It has been identified that the supply air and return air to the plant has been arranged with a single duct for each zone. The network of ducting inside the building is also limited especially for return air, but all ducts seem to be fully insulated for both the supply and return air stream duct network.

From the documentation provided, it is noted that the original Direct Expansion DX refrigeration plant was unreliable due to a long service of more than 25 years reducing the suitability for accurate control of temperature and humidity. The heating and humidifying system was electric making it costly and unreliable. The design of the building is mostly well insulated with apparently low levels of infiltration based on its homogenised layout which reduces airflow irregularities; nevertheless, it has been pointed out that a lack of uniform temperature and humidity in the whole space might be restricted by racks and artwork positioned in locations where the airflow can be fluctuated as shown in figures 3.3 and 3.4. Some monitoring of temperature and humidity are to be added and installed at multiple locations to be controlled by a logic Building Management System (BMS).

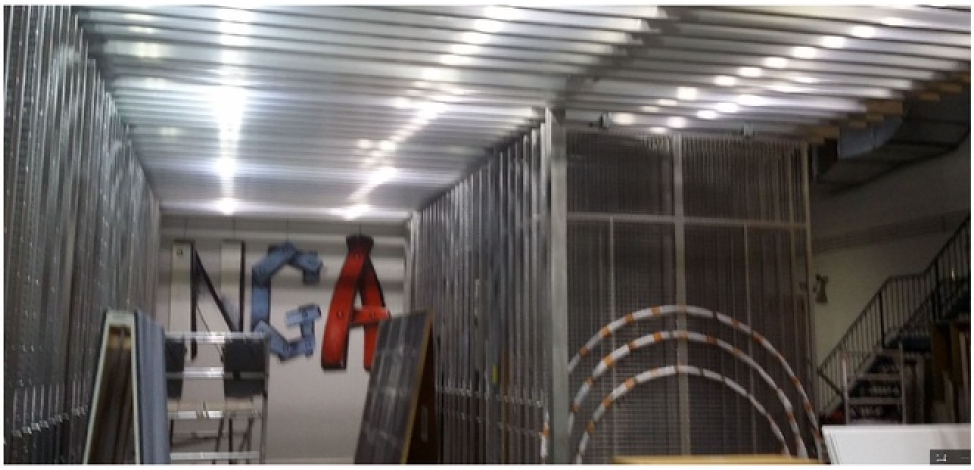


Figure 4.3. Rack structure within the NGA off-site facility

Figure 4.4. Rack structure within the NGA off-site facility

During the visits to the off-site facility, it was observed that a major proportion of the condensation issues are located in the section where paintings, objects and paper are stored, (see appendix C for reference). The following covers 80% of the identified condensation issues, so the analysis was focused on these areas, and the investigation was developed based on the condition of these sections as a whole covering the central and east sides of the building. A detailed analysis of the HVAC system is out of the scope of the condensation project, nevertheless, additional information is given to provide a clearer understanding of the overall system. The following components are to be replaced: original Air Handling Unit number 2 of 3 (AHU), heating coils, cooling coils and a plug fan driven by a Variable Speed Drive (VSD). The following is a summary of the parameters for this upgrade:

Reference	AHU-2 Cooling	AHU-2 Heating
Total Supply Air Quantity (L/s)	19000	19000
Supply Air Quantity for Smoke Mode (L/s)	24000	24000
Return Air Quantity Through Mixing Plenum (L/s)	18000	18000
Minimum Outside Air (L/s)	1000	1000
Air flow Rate at the Coil (L/s)	10000	19000

Approximated External System Resistance (Pa)	520	520
Approximated Motor (KW)	22-30	22-30
Drive type	Impeller direct on shaft, VSD Driven	Impeller direct on shaft, VSD Driven
Approximated Total Capacity (KW)	200	183

Table 4.1. Specifications for Air Handling Unit 2 (AHU-2).

It is important to mention that the smoke control system and smoke exhaust has been taken into account for the HVAC upgrade, but they have not been introduced in this project as it is not relevant for the development of the condensation investigation. Also, the condensation analysis is based on the central and east zone where condensation has been reported.

4.3 Condensation in the facilities

The problem of condensation has been addressed through documentation, personnel survey and visual evidence as shown in figure 4.5.

Figure 4.5. Condensation marks on the floor marked by personnel.

The most recent condensation issues have been related to the ceiling void and H-sections between the cool room panels of the internal ceiling despite its characteristics of improved air barrier penetration for infiltration and exfiltration in the building enclosure. This phenomenon is more noticeable on cold days and during extremely prolonged winters. The tracking of this condensation has led to drips into the space in different areas of the facility. During inspection, the detachment of the vapour seal tapes in some areas of the ceiling where the cooling panels meet was noticeable as shown in figures 4.6 to 4.11.

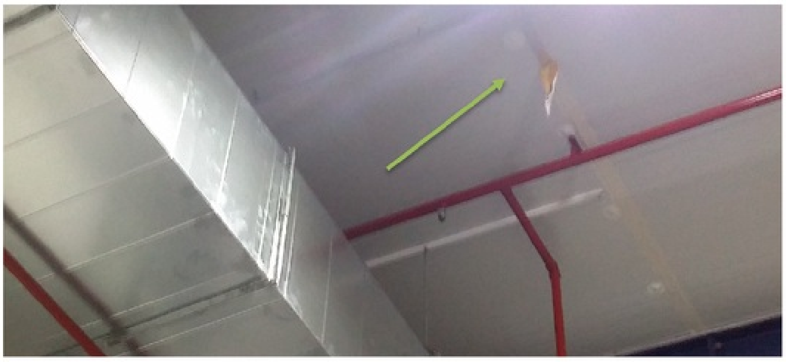


Figure 4.6. Detachment of vapour seal tape 1 in the ceiling panel joint.

Figure 4.7. Detachment of vapour seal tape 2 in the ceiling panel joint.

Figure 4.8. Detachment of vapour seal tape 3 in the ceiling panel joint.

Figure 4.9. Detachment of vapour seal tape 4 in the ceiling panel joint.

Figure 4.10. Detachment of vapour seal tape 5 in the ceiling panel joint.

Figure 4.11. Detachment of vapour seal tape 6 in the ceiling panel joint.

The investigation aims to understand the thermal efficiency of related materials and trace the correct insulation installation through the building and ductwork despite the proposed plan of insulating the uninsulated duct in the plan room to minimize condensation and energy loss. Ideally, an airtightness test would narrow the possibilities of air leakage and water vapour in the building, but nothing has been done until now, and the suitability of a pressurization test in a space with extremely valuable items and the effect it can have on the contents has not been documented. Although these tests are recommended, they are not mandatory under the Australian regulations or Building Construction Code. However, it is of interest to acknowledge the changes in the air flow induced by hatches, perforations of screws, bolts, ducts and fittings especially in the ceiling/roof composite.

4.4 Measurements

The surface temperature and relative humidity inside and outside the NGA off-site facility were measured at different points and locations. The results shown are average values that determine the conditions during that particular date.

Internal Reading Location (13/09/2016)	West Store Area		Central Store Area (Lower Floor)		Central Store Area (Upper Floor)		East Store Area	
	Temperature	Relative Humidity	Temperature	Relative Humidity	Temperature	Relative Humidity	Temperature	Relative Humidity
	Avg.(°C)	Avg.(%)	Avg.(°C)	Avg.(%)	Avg.(°C)	Avg.(%)	Avg.(°C)	(%)
Supply Air	21		20.1		21.2		20.9	
Ceiling	20.9		N/A		19.2		20.1	
Cross Beam	20.1		19		18.7		19.3	
Vapour Seal tape	20.7	55.3	19.7		19.7		19.3	
Wall	20.7		N/A	53	19.4	55.1	19.8	50.5
Intersection Beam and Wall	18.4		N/A		18.6		19	
Intersection Wall and Floor	17.3		19.7		N/A		18	
Storage Racks	21.1	54.7	N/A		N/A		N/A	

Table 4.2. Internal measurements of temperature and relative humidity.

External Reading Location (13/09/2016)	West		North		South		East	
	Temperature	Relative Humidity	Temperature	Relative Humidity	Temperature	Relative Humidity	Temperature	Relative Humidity
	Avg.(°C)	Avg.(%)	Avg.(°C)	Avg.(%)	Avg.(°C)	Avg.(%)	Avg.(°C)	(%)
Outside Air Conditions	14.6		14.8		14.9		14.9	
Ceiling	N/A		N/A		N/A		N/A	
Smoke Exhaust Outlet	16.3	67.8	N/A	68	N/A	67.6	16	68.9
Structural Bolts	11.6		12.3		N/A		10.6	
Wall	20.7		8.8		13		10	
Intersection Wall and Gutter	12.3		10.5		12.8		10.2	

Table 4.3. External measurements of temperature and relative humidity.

4.5 Psychrometric Analysis

POINT	LABEL	AIR FLOW	UOM	PROCESS	GIVEN	DB	WB	RH	W	V	H	DP	D	VP	AW
Outside Air	AR	1000	STD L/S	Add State Point	POINT	34.0	21.0	30.8	10.3	0.88	60.54	14.4	1.1428	12.315	11.633
Room Air	AL	18000	STD L/S	Add State Point	POINT	22.0	16.1	55.0	9.1	0.85	45.23	12.6	1.1900	10.912	10.727
Mixed Air Phase (1)	AR	19000	STD L/S	Air Mixing	POINT	22.6	16.4	53.3	9.2	0.85	46.03	12.7	1.1875	10.986	10.776
On-Coil Air	BR	10000	STD L/S	Add State Point	POINT	22.6	16.4	53.3	9.1	0.85	45.95	12.6	1.1876	10.963	10.755
By-pass Air	BR	9000	STD L/S	Add State Point	POINT	22.6	16.4	53.3	9.1	0.85	45.95	12.6	1.1876	10.963	10.755
Off-Coil Air	BR	10000	STD L/S	Cooling Coil	POINT	6.3	6.3	100.0	5.9	0.80	21.26	6.3	1.2592	7.162	7.435
Mixed Air Phase (2)	BR	19000	STD L/S	Air Mixing	POINT	14.0	11.5	74.7	7.5	0.82	32.93	9.6	1.2243	8.967	9.059

Table 4.4. Psychrometric Analysis for Summer.

$$Mixed\ Air\ Phase\ (1) = (\%\ Room\ Air * T°\ Room\ Air) + (\%\ Outside\ Air * T°\ Outside\ Air)$$

$$Mixed\ Air\ Phase\ (1) = (95\% * 22\ °\mathrm{C}) + (5\% * 34\ °\mathrm{C}) = 22.6\ °\mathrm{C}$$

$$Q = V * \rho * C_p * \Delta T$$

$$T_{On-Coil} - T_{Off-Coil} = \frac{Q}{V * \rho * C_p}$$

$$T_{Off-Coil} = T_{On-Coil} - \frac{Q}{V * \rho * C_p}$$

$$T_{Off-Coil} = 22.6°\mathrm{C} - \frac{200\ \frac{KJ}{s}}{10\ \frac{m^3}{s} * 1.02\frac{Kg}{m^3} * 1.2\frac{KJ}{Kg°\mathrm{C}}}$$

$$\boldsymbol{T_{Off-Coil} = 6.26}\ °\mathrm{C} \approx \boldsymbol{6.3}\ °\mathrm{C}$$

$$Mixed\ Air\ Phase\ (2) = (\%\ Off-Coil\ Air * T°\ \ Off-Coil\ Air) + (\%\ By-Pass\ Air * T°\ By-Pass\ Air)$$

$$Mixed\ Air\ Phase\ (2) = (52\% * 6.3\ ℃) + (48\% * 22.6\ ℃) \approx 14\ ℃$$

$$\boldsymbol{Mixed\ Air\ Phase\ (2) = Supply\ Air \approx 14}\ ℃$$

$$Moist\ Air\ Phase\ (2) = (\%\ Off - Coil\ Moist * W\ \ Off - Coil\ Moist) + (\%\ By - Pass\ Moist * W\ By - Pass\ Moist)$$

$$Mixed\ Air\ Phase\ (2) = \left(52\% * 5.9\frac{g}{Kg\ DA}\right) + \left(48\% * 9.1\frac{g}{Kg\ DA}\right) \approx 5.9\frac{g}{Kg\ DA}$$

$$\boldsymbol{Moist\ Air\ Phase\ (2) = Supply\ Moist \approx 7.5\frac{g}{Kg\ DA}}$$

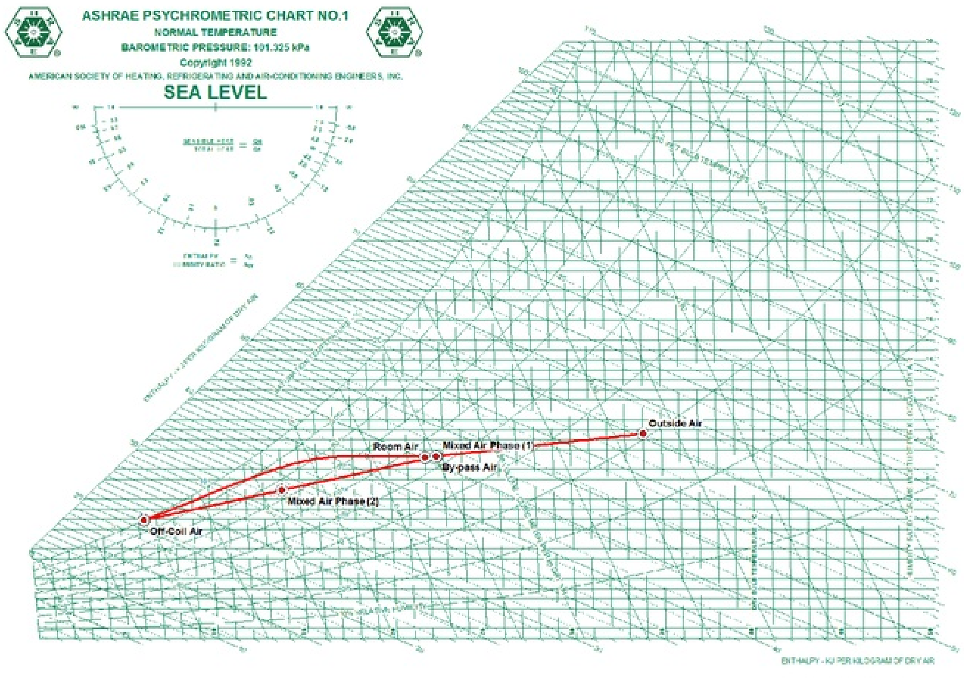


Figure 4.12 Pshychrometric plot for winter conditions.

POINT	LABEL	AIR FLOW	UOM	PROCESS	GIVEN	DB	WB	RH	W	V	H	DP	D	VP	AW
Outside Air	AR	1000	STD L/S	Add State Point	POINT	-4.0	-4.0	100.0	2.7	0.77	2.73	-4.0	1.3099	3.281	3.538
Room Air	AR	19000	STD L/S	Add State Point	POINT	22.0	16.1	55.0	9.1	0.85	45.23	12.6	1.1900	10.912	10.727
Return Air	AL	18000	STD L/S	Add State Point	POINT	22.0	16.1	55.0	9.1	0.85	45.23	12.6	1.1900	10.912	10.727
Mixed Air Phase (1)	L	19000	STD L/S	Air Mixing	POINT	20.6	15.4	57.6	8.8	0.84	42.98	12.0	1.1958	10.515	10.384
On-Coil	B	19000	STD L/S	Add State Point	POINT	20.6	15.4	58.1	8.8	0.84	43.09	12.1	1.1959	10.585	10.454
Off-Coil - Supply Air	B	19000	STD L/S	Sensible Heating	POINT	28.5	18.2	36.2	8.8	0.87	51.16	12.1	1.1646	10.585	10.180

Table 4.5 Psychrometric Analysis for Winter.

$$Mixed\ Air\ Phase\ (1) = (\%\ Room\ Air * T°\ Room\ Air) + (\%\ Outside\ Air * T°\ Outside\ Air)$$

$$\boldsymbol{Mixed\ Air\ Phase\ (1) = (95\% * 22\ ℃) + (5\% * -4\ ℃) = 20.6\ ℃}$$

$$Q = V * \rho * C_p * \Delta T$$

$$T_{On-Coil} - T_{Off-Coil} = \frac{Q}{V * \rho * C_p}$$

$$T_{Off-Coil} = T_{On-Coil} - \frac{Q}{V * \rho * C_p}$$

$$T_{Off-Coil} = 20.6℃ - \frac{183\ \frac{KJ}{s}}{19\ \frac{m^3}{s} * 1.02 \frac{Kg}{m^3} * 1.2 \frac{KJ}{Kg℃}}$$

$$\boldsymbol{T_{Off-Coil} = 28.5\ ℃}$$

$$Moist\ Air\ Phase\ (1) = (\%\ Return\ Moist * W\ \ Return\ Moist) + (\%\ Outside\ Moist * W\ Outside\ Moist)$$

$$Mixed\ Air\ Phase\ (1) = \left(95\% * 9.1 \frac{g}{Kg\ DA}\right) + \left(5\% * 2.7 \frac{g}{Kg\ DA}\right)$$

$$\boldsymbol{Moist\ Air\ Phase\ (1) = Supply\ Moist \approx 8.8 \frac{g}{Kg\ DA}}$$

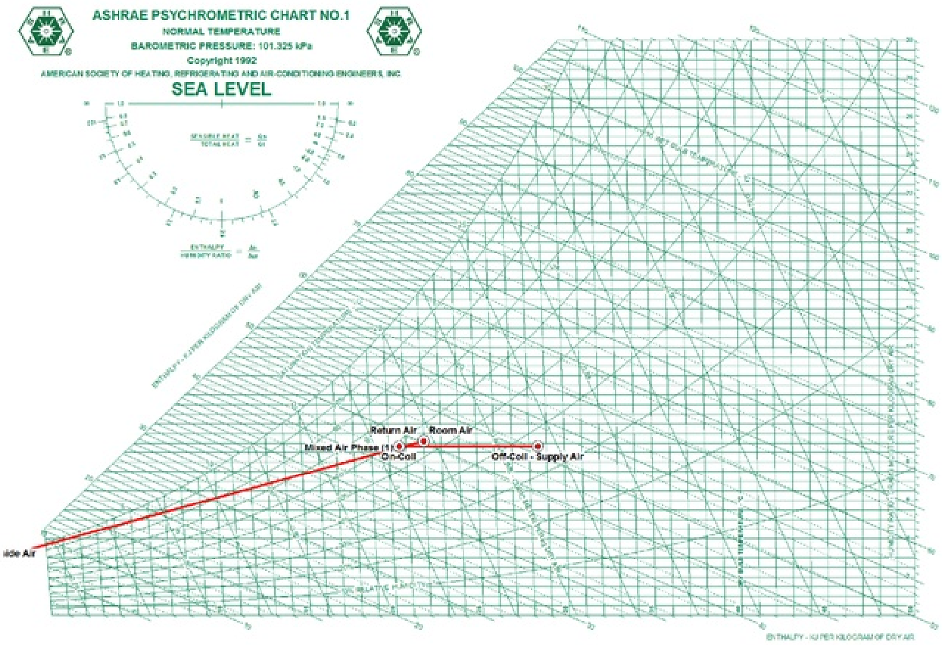


Figure 4.13 Pshychrometric plot for winter conditions

4.6 Ventilation and Airflow

The upgrade and design of the AHU serving the central and east storage sections may affect the maintainability of the required internal conditions. For this reason, an approach to the design parameters was analysed in order to understand the relationship between ventilation and condensation.

A total approximated area of 1720 m2 and approximated average high of 6 metres is covered by the central and east storage rooms. In order to identify the openable area or leakage estimated by the current design, it is necessary to determine if the pressurisation flow rate used for this section matches with the air changes presented in table 4.6. The average pressure difference for this type of calculations is taken to be 50 Pa (CIBSE TM23, 2000) and means that the building has been constructed with an acceptable rate infiltration. For the purpose of this analysis equations 19 and 20 are used.

$$M\dot{V} = \dot{V}_{space}\,AC\; = 1720\,m^2 * 7\,m * \frac{0.25}{h} = \;3010\,\frac{m^3}{h} = \;836\,L/s$$

Air permeability / ($m^3/m^2{\cdot}h$ at 50 Pa)	Infiltration rate (ACH) for given building size / h^{-1}							
	500 m^2 (25 m × 20 m × 5 m)*		1500 m^2 (50 m × 30 m × 10 m)*		5000 m^2 (100 m × 50 m × 20 m)*		10000 m^2 (100 m × 100 m × 25 m)*	
	Peak	Average	Peak	Average	Peak	Average	Peak	Average
20.0 (leaky)	1.00	0.65	0.75	0.45	0.55	0.35	0.45	0.30
10.0 (Part L (2002))	0.50	0.35	0.40	0.25	0.30	0.20	0.25	0.15
7.0 (Part L (2005))	0.30	0.25	0.25	0.15	0.20	0.15	0.15	0.10
5.0	0.20	0.20	0.20	0.15	0.15	0.10	0.15	0.10
3.0	0.15	0.10	0.15	0.10	0.10	0.05	0.10	0.05
Air change rate at 50 Pa (/ h^{-1})		5.80		3.05		1.60		1.20
ACR_{50} divisor		18.7		13.6		10		9.2

* (length × width × height) = 40 m × 25 m × 4 m for each storey (all cases)

Table 4.6. Air changes for a warehouse [35].

The calculated value approximates the make-up air design volume of 1000 L/s for air permeability. The calculated value is the minimum flow rate and the leakage area can be approximated to different pressure gradients.

$$A = \frac{\dot{V}_{space}}{840\,(\Delta P)^{1/2}}$$

Make-up Air flow = 836 L/s						
ΔP (Pa)	5	10	20	30	40	50
A (m^2)	0.45	0.31	0.22	0.18	0.16	0.14
Make-up Air flow = 836 L/s						
ΔP (Pa)	5	10	20	30	40	50
A (m^2)	0.53	0.38	0.27	0.22	0.19	0.17

Table 4.7. Approximated leakage area.

From the results obtained above, it is observed that the total openable area or leakage is approximately 150 mm squared at a standard pressure of 50 Pa. Any reduction in this pressure shows an increase of the openable area. However, this is a calculated approximation, and for a more accurate result, a pressurization test on-site is required.

The pressure due to the wind in the roof is of interest to this investigation, and it is calculated using data from table 2.2, equations 17 and 18. Atmospheric data for the Canberra region where the NGA off-site facility is located was obtained from the Bureau of Meteorology for the month of July 2016 and is shown in Table 4.8. The month of July was purposely selected as it is in the middle of winter where condensation is more likely to occur.

Determining the velocity of the wind at different heights of the 3° pitched roof from ground level at some wind speeds reported during July 2016. The base of the roof is at 6 metres while the highest point is at 7.5 metres.

		Temps		Rain	Evap	Sun	Max wind gust			9 am						3 pm					
Date	Day	Min	Max				Dir	Spd	Time	Temp	RH	Cld	Dir	Spd	MSLP	Temp	RH	Cld	Dir	Spd	MSLP
		°C	°C	mm	mm	hours		km/h	local	°C	%	8th		km/h	hPa	°C	%	8th		km/h	hPa
1	Fr	-0.4	11.6	1.0			NW	48	00:03	5.7	79		NNW	17	1016.4	10.5	60	2	NNW	20	1018.5
2	Sa	-3.8	13.3	0.2			WNW	35	16:25	1.4	91			Calm	1027.4	12.6	49		WNW	20	1024.4
3	Su	-5.2	12.9	0			NNW	35	16:22	0.2	95		NW	7	1027.5	12.5	56		NNW	20	1023.4
4	Mo	-2.4	8.4	0			N	17	14:39	2.5	99	8	SSE	7	1021.3	8.1	74	8	NNE	7	1017.5
5	Tu	0.3	8.0	4.8			NW	35	16:39	4.6	99	8	ESE	9	1012.4	7.9	97	8	SSW	7	1007.7
6	We	4.4	11.3	18.0			NW	39	12:26	6.2	90	7	WNW	22	1006.3	9.5	84	8	N	9	1006.9
7	Th	6.2	14.6	0.4			S	41	11:25	11.3	77	3	S	15	1020.0	14.6	54	5	SSW	19	1019.8
8	Fr	2.8	13.2	0			SSW	19	10:15	7.8	88	8	SSE	7	1022.5	12.2	73	8	SE	13	1020.3
9	Sa	3.6	13.1	1.0			W	17	12:36	8.1	92	8		Calm	1025.7	11.9	69	6	N	13	1023.7
10	Su	1.9	13.8	0			NNE	24	14:13	8.4	87	7	ESE	7	1026.2	13.0	62	5	NNE	13	1021.0
11	Mo	7.8	13.4	9.8			NW	50	15:10	9.8	88	8	N	19	1014.3	13.0	71	1	NW	35	1010.2
12	Tu	6.7	11.2	0.8			NNW	91	16:48	7.7	84	8	NNW	28	1010.8	9.7	67	6	NW	43	1006.0
13	We	0.6	7.1	4.8			WNW	69	11:22	2.2	83	3	NW	31	1016.8	5.6	56	7	WNW	20	1021.6
14	Th	0.6	11.2	0			WNW	48	15:12	4.8	69		N	17	1030.1	10.4	40		WNW	31	1026.8
15	Fr	-3.1	13.1	0			N	30	01:56	1.8	82		SE	9	1032.0	12.7	41		NW	4	1028.7
16	Sa	-3.0	16.1	0.2			N	17	16:19	2.5	87		N	7	1034.7	15.4	49		NNW	9	1030.6
17	Su	1.1	16.2	0			NW	22	14:37	3.2	99	8	S	6	1033.1	15.8	54		WNW	15	1028.3
18	Mo	-1.8	17.6	0.2			NW	56	12:21	6.7	99		S	4	1026.0	16.0	66	3	W	22	1023.2
19	Tu	6.7	18.8	2.6			NW	35	12:48	13.8	96	8	N	17	1023.8	16.7	78	2	NNW	20	1021.7
20	We	11.1	14.4	8.6			SW	20	06:06	11.8	99	8	ESE	9	1021.8	14.1	79	7	NNE	11	1021.8
21	Th	8.5	14.9	0.2			NNW	24	16:58	10.1	97	8	SW	6	1022.1	13.7	76	8	NW	7	1017.4
22	Fr	9.6	16.9	0.6			NNW	78	13:27	13.7	99	8	NW	33	1008.5	16.3	87	8	NNW	52	999.0
23	Sa	4.7	10.4	3.6			WNW	76	01:06	6.9	77	2	NW	35	1002.5	8.0	58	8	N	20	1007.2
24	Su	-2.2	8.4	0.2			W	48	20:16	3.8	74			Calm	1016.2	7.6	58	7	NNW	22	1011.4
25	Mo	3.2	10.9	8.4			NW	54	16:41	6.6	82	2	NW	30	1012.4	8.6	68	8	NW	28	1013.0
26	Tu	4.5	10.2	0.2			NW	65	00:14	6.2	71		NW	30	1016.1	9.8	54	7	NW	30	1013.6
27	We	4.6	11.8	5.2			WNW	43	14:25	7.0	88	8	NNW	28	1012.3	11.4	62		WNW	26	1015.4
28	Th	1.4	12.6	0			WNW	41	17:09	6.1	78		N	15	1025.4	12.3	52		WNW	26	1023.3
29	Fr	-3.4	12.8	0.2			NW	41	14:52	5.0	85		ESE	6	1024.3	11.7	60		NW	31	1020.5
30	Sa	-1.0	11.9	0			NNW	26	15:29	3.4	99	8	N	6	1025.4	11.6	61		N	15	1021.2
31	Su	3.3	14.9	0			W	43	09:22	9.7	76		NW	20	1019.0	14.0	65	4	NNW	20	1017.4
Statistics for July 2016																					
Mean		2.2	12.7							6.4	87	6		14	1020.4	11.8	63	6		20	1018.1
Lowest		-5.2	7.1	0						0.2	69	2		Calm	1002.5	5.6	40	1	NW	4	999.0
Highest		11.1	18.8	18.0			NNW	91		13.8	99	8	NW	35	1034.7	16.7	97	8	NNW	52	1030.6
Total				71.0																	

IDCJDW2801.201607 Prepared at 13:02 GMT on Monday 17 October 2016

Table 4.8. Statistical weather observations from Canberra airport for July 2016 [37].

Date	Wind Direction	Wind Speed	Wind Speed	Terrain constant	Height	Terrain constant	Wind speed at Building Height (Vz)	Density of Air	Wind Pressure Coefficient	Square Vz	Surface Pressure due to Wind
		(km/h)	(m/s)	k	(m)	a	(m/s)	(Kg/m^3)	(-)		(Pa)
3rd July 2016 3:00 pm	NNW	20	5.56	0.68	6	0.17	5.12	1.2	-0.5	26.24	-7.87
					6.5		5.19			26.97	-8.09
					7		5.26			27.66	-8.30
					7.5		5.32			28.31	-8.49
12th July 2016 4:48pm	NNW	91	25.28		6		23.31			543.33	-163.00
					6.5		23.63			558.32	-167.50
					7		23.93			572.57	-171.77
					7.5		24.21			586.16	-175.85
22nd July 2016 3:00 pm	NNW	52	14.44		6		13.32			177.42	-53.22
					6.5		13.50			182.31	-54.69
					7		13.67			186.96	-56.09
					7.5		13.83			191.40	-57.42

Table 4.9. Surface pressure due to wind.

The results show that the surface pressure is negative on the roof as expected. However, this pressure has an exponential increase that can lead to a fast exfiltration of air because of the wind if the tightness and seal of the building is not adequate.

To understand the building behaviour better, the surface pressure due to stack effect is also determined ignoring the force ventilation. The stack effect pressure is calculated assuming two vertical openings. One at a lower height which is normally found on doors and gates and the other at the roof height. This estimation provides information about the imbalance pressure due to possible temperature differences during winter design and the contribution it can have to the wind surface pressure.

Lower Opening Above Ground	Upper Opening Above Ground	Inside Temperature	Outside Temperature	Stack Pressure	Outside Temperature	Stack Pressure	Outside Temperature	Stack Pressure
(m)	(m)	(°C)	(°C)	(Pa)	(°C)	(Pa)	(°C)	(Pa)
0.02	6	22	-4	-6.769	0	-5.644	10	-2.970
	6.5			-7.335		-6.116		-3.218
	7			-7.901		-6.588		-3.466
1	6			-5.660		-4.719		-2.483
	6.5			-6.226		-5.191		-2.731
	7			-6.792		-5.663		-2.980
2	6			-4.528		-3.775		-1.986
	6.5			-5.094		-4.247		-2.235
	7			-5.660		-4.719		-2.483

Table 4.10 Surface pressure due to stack effect.

4.7 Interstitial Condensation Analysis

One of the requirements in the NGA off-site facility is that the temperature and relative humidity must be maintained at 22°C ±1.5 °C and 55% ±5% respectively. These settings are to be kept 24/7 during the 365 days of the year. The measurement of these conditions in relation to the external environment provides an indication of climate control and equipment operation. Therefore, they are important for the effectiveness of the control and transfer of moisture conditions. The presence of water vapour pressure from areas of high moisture content to low moisture content is more critical in this kind of building as it contributes to creating a stack effect due to the lack of mechanical ventilation in the upper sections near the ceiling- roof composite.

The following calculations were made to identify any possibility of interstitial condensation within the composite materials of the roof under design conditions. Normally, this type of condensation is seen on fabrics where two layers of material intersect and its location is referenced as a node. Condensation will occur if the vapour pressure at the node equals the saturated pressure of the temperature at that node.

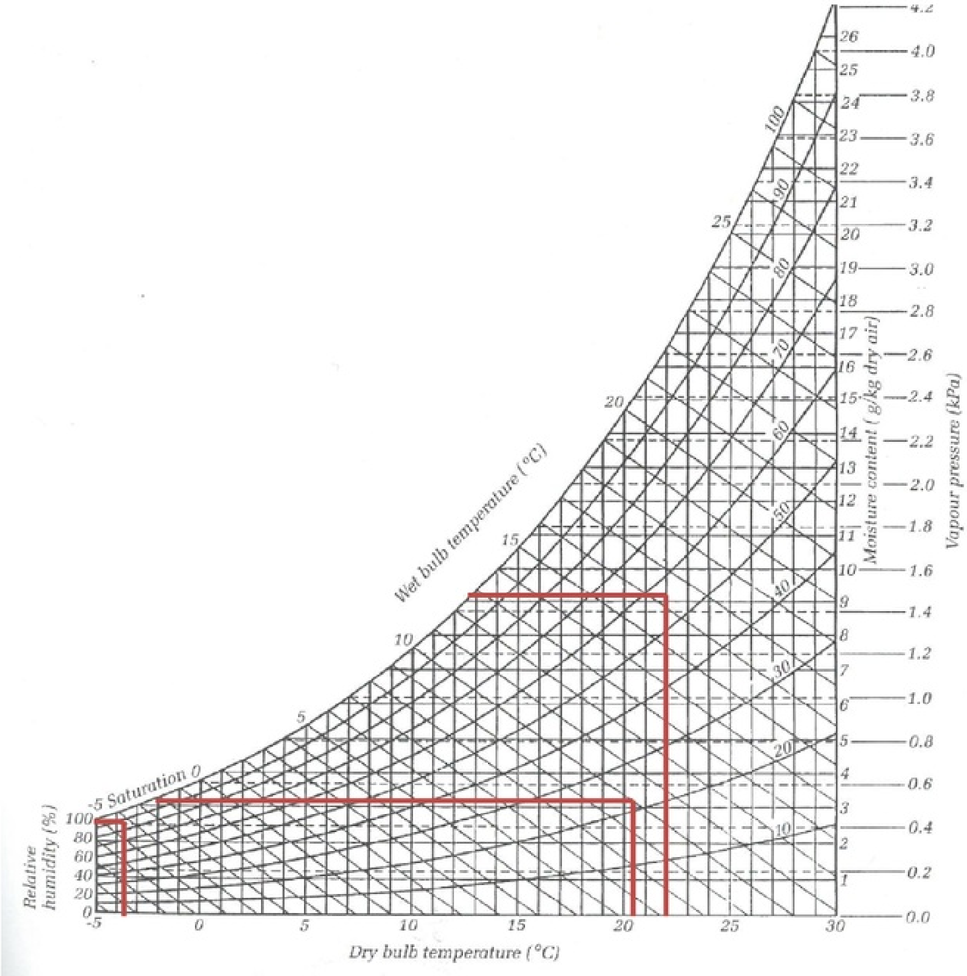


Figure 4.14 Material layer dew poin in the psychrometric chart.

	Temperature	Relative Humidity - RH	Vapour Pressure
	(°C)	(%)	(KPa)
External	-4	100	0.4371
Internal	22	55	1.4549
Difference	26	45	1.0178

Table 4.11 Vapour pressure design parameters.

	Thickness	Thermal Conductivity	Vapour Resistivity	Thermal Resistance	Vapour Resistance
	d	λ	r	R	G
	(m)	(W/m °C)	(GNs/Kgm)	(m^2 °C/W)	(GNs/Kg)
		Table	Table	R = d / λ	G = d * r
Exterior Surface	n/a	n/a	0	0.06	0
Roof (Steel-Zinc coated)	0.0006	50	∞	0.000012	0
fibreglass Insulation	0.15	0.04	7	3.750000	1.05
Polyesterene Insulation	0.06	0.35	300	0.171429	18
Interior Surface	n/a	n/a	0	0.012	0
Total	**0.2106**	**50.39**	**n/a**	**3.99**	**19.05**

Table 4.12 Thermal and vapour resistances.

	Temperature	Vapour Pressure	Saturated Vapour Pressure	Relative Humidity	Dew Point
	Tn	Pv	Ps	RH	Dp
	(°C)	(Kpa)	(Kpa)	(%)	(°C)
	$T_n = T_{si} - \left[\frac{((T_{si} - T_{se}) * \sum_{si}^{n} R)}{\sum_{si}^{se} R}\right]$	$P_v = P_{vsi} - \left[\frac{((P_{vsi} - P_{vse}) * \sum_{si}^{n} G)}{\sum_{si}^{se} G}\right]$	Calculated using Michell Instruments Calculator	RH = Pv/Ps	Psychrometric chart
Inside	22	1.4549	2.6453	55.0	12.555
node 1 (Inside / Poyestyrene insulation)	21.92	1.4549	2.6324	55.3	12.554
node 2 (Poyestyrene insulation / Fibreglass Insulation)	20.81	0.4932	2.4592	20.1	-2.917
node 3 (Fibreglass Insulation / Roof)	-3.61	0.4371	0.4521	96.7	-4.4799
node 4 (Roof / Outside)	-3.61	0.4371	0.4470	97.8	-4.4527
Outside	-4	0.4371	0.4375	99.9	-4.517

Table 4.13 Temperature and vapour pressure through the layers.

4.8 Thermal Bridging Analysis

The following numerical calculations are solely for the roof composite and its structure. Condensation has been said to be located on the roof; therefore, the analysis has been focused only on this section of the building. The minimum values or thermal resistance are provided by the Building Code of Australia for different zones and building class in Australia as shown in figure 2.3. In order to comply with these standards, the total thermal resistance (R) and the rate of heat transfer (U – value) for the composite roof is calculated using the calculator provided by Vesma [38] for this purpose.

Condensation on any surface is predicted to be formed when the moist air contained within the designed space gets in contact with a colder surface. This contact reduces the capability of the air to hold moisture, and it is defined as the reach of the dew point. Figure 4.15 shows part of the front view plan to identify some of the materials for the following calculations.

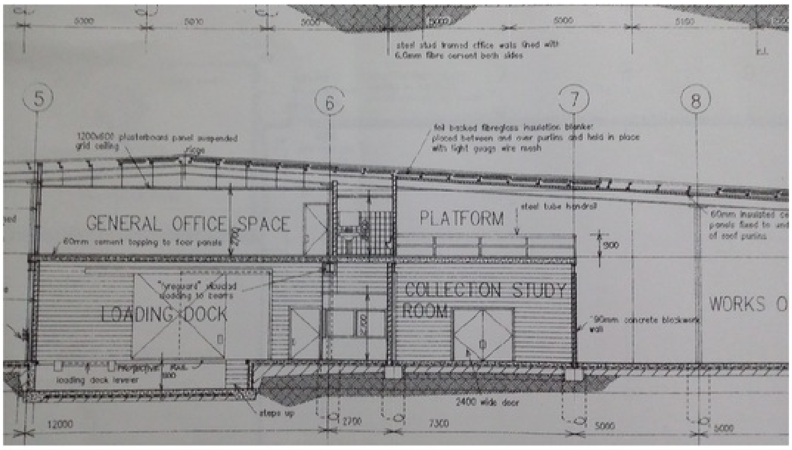


Figure 4.15. NGA off-site facility front view with some structural and materials details.

The following calculations in the figures below present R-values and U-values for the composite roof at the NGA off-site facility in the section where no structural material is present under winter design conditions only. It is important to mention that Ebonite is introduced as a substitute of polystyrene as the interior insulation material. The reason for doing so is that polystyrene is not available within the list of optional materials at Vesma. However, the value of thermal conductivity of ebonite lies between the guide values for extruded polystyrene (0.03 to 0.04 W/mK) suggested from different sources [25] and presented in appendix E, Apache table.

Element and exposure

Element:	Roof
Exposure:	Normal

Conditions

	Temp C	RH %
Internal:	22	55
External:	-4	100

Details of structure

Layer	Thickness (mm)	Conductivity (W/mK)	Resistance (m2K/W)	Condensation risk?
Internal surface			0.10	
Ebonite	60	0.037	1.62	
Glassfibre	150	0.040	3.75	
Steel	1	50.000	0.00	*
		-	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
External surface			0.04	
	Total resistance		5.51	m^2K/W

U-VALUE	**0.18**	W/m^2K

Figure 4.16. Analysis of homogeneous layers for the composite materials.

The total thermal resistance of 5.51 m^2k/W for the composite roof presents compliance with the BCA required minimum value of 3.7 m^2k/W. Nevertheless, any contact of internal design air with the roof internal surface will cause condensation.

A more detailed approach to the roof was considered in terms of structural condition to determine the possibility of thermal bridging within the installations. Additional analysis was performed to the sections shown in figure 4.18 and figure 4.20. In order to have a more detailed perspective of under which conditions condensation can occur in any other surface of the composite roof, the following calculations were made.

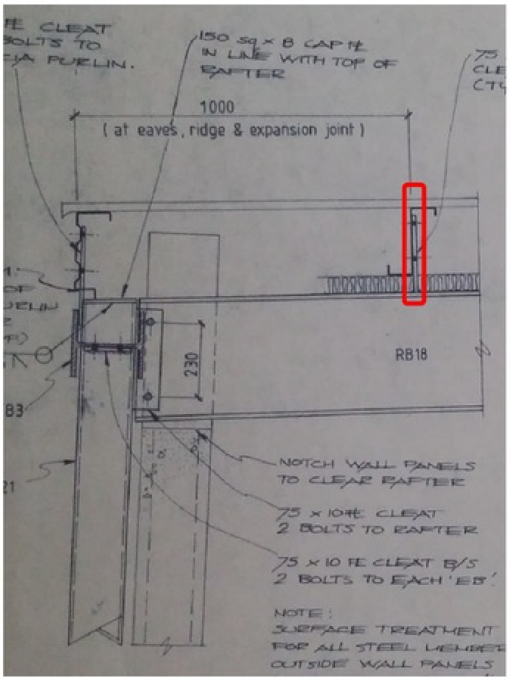


Figure 4.17 Purlin cleat.

Element and exposure

Element:	Roof
Exposure:	Normal

Conditions

	Temp C	RH %
Internal:	22	55
External:	-4	100

Details of structure

Layer	Thickness (mm)	Conductivity (W/mK)	Resistance (m2K/W)	Condensation risk?
Internal surface			0.10	
Steel	185	50.000	0.00	*
Cavity	15	-	0.18	
Steel	1	50.000	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
External surface			0.04	
	Total resistance		0.32	m^2K/W

U-VALUE	3.09	W/m^2K

Figure 4.18 Analysis at the purlin cleat assembly.

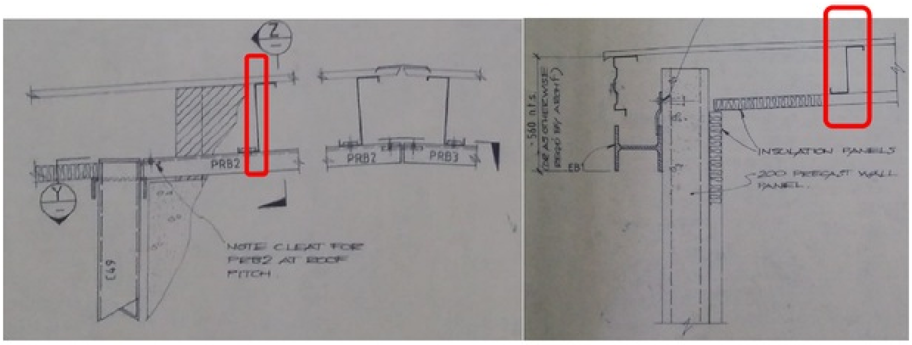


Figure 4.19 Purlin arrangement within the structure.

Element and exposure

Element:	Roof
Exposure:	Normal

Conditions

	Temp C	RH %
Internal:	22	55
External:	-4	100

Details of structure

Layer	Thickness (mm)	Conductivity (W/mK)	Resistance (m2K/W)	Condensation risk?
Internal surface			0.10	
Ebonite	60	0.037	1.62	
Steel	150	50.000	0.00	*
Steel	1	50.000	0.00	
		-	0.00	
		-	0.00	
		-	0.00	
	0	-	0.00	
		-	0.00	
External surface			0.04	
	Total resistance		1.76	m^2K/W

U-VALUE	**0.57**	W/m^2K

Figure 4.20 Analysis for purlin within the structure.

In figure 4.19 and 4.21 it is possible to determine the lack of thermal resistivity within the structural arrangement. In either case a layer of insulation is dismissed and the total thermal resistance and U-values are decreased considerably. The values determined for these structural arrangements give a good indication of the location where condensation originates from.

4.9 Thermal Modelling

A 3D Modelling of the building in Revit 2016 from floor plan drawings supplied by the department of services has been done to have a better understanding of the structural layouts and to identify where the I-beams interconnect. In addition to visualize the total area covered by the purlins.

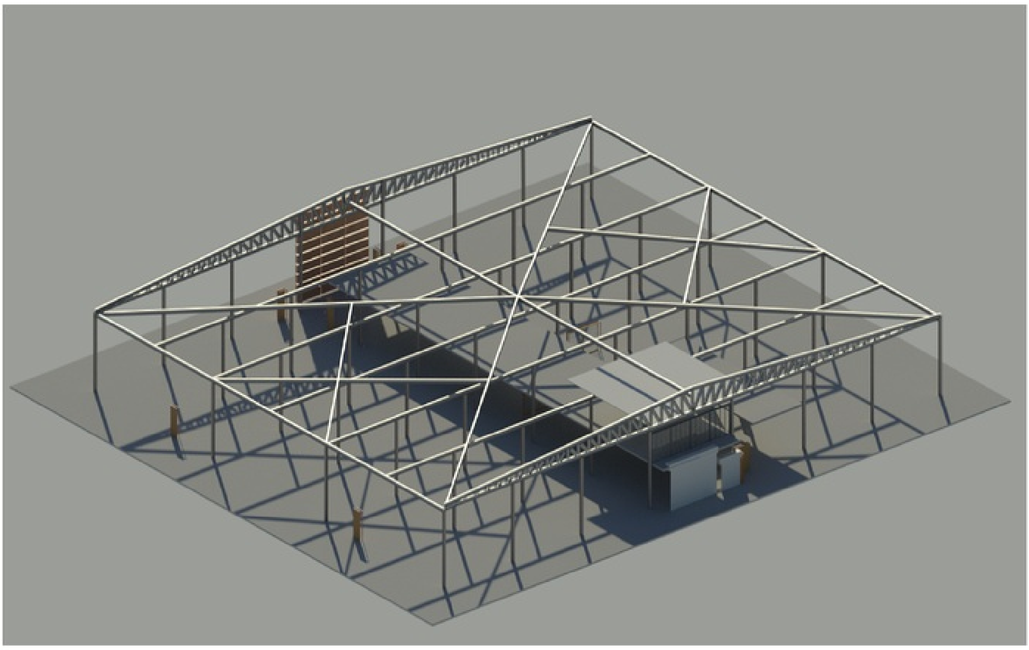


Figure 4.21. 3D structural model in Revit.

The homogenous section of the roof containing the I-beam, the cool panel of polystyrene, the fibreglass quilt and the metallic roof was modelled in steady state using Ansys 17.2 student version and shown in figure 4.22 to understand and predict the thermal distribution of the ceiling/roof composite. The thermal resistance values were set accordingly to the specific materials and the temperature boundaries set to the design conditions during winter. Similarly, a section where the purlin is attached to the beam by the purlin cleat as shown in figure 4.17 is modelled in figure 4.23.

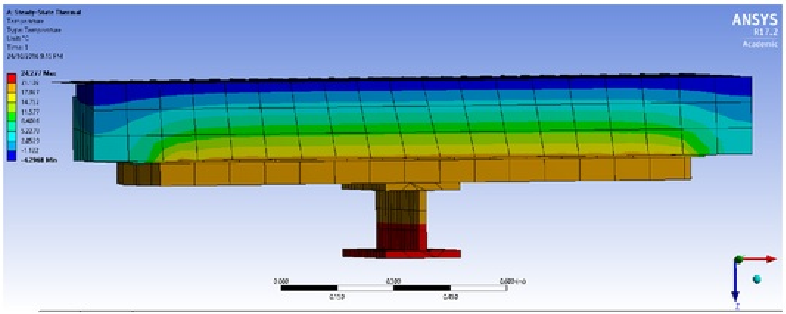


Figure 4.22. Thermal distribution of homogenous section.

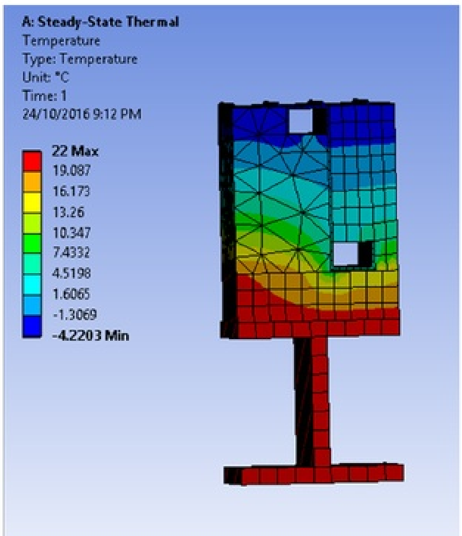


Figure 4.23. Thermal distribution at the purlin section.

A more detailed model was analysed using Heat3 in order to validate the calculated results and the predicted condensation due to thermal bridging. The thermal model shown in figure 4.25 confirms the potential of surface condensation at points (1) where the I-beam penetrates the internal wall insulation and (2) where the roof is fixed to the I-beam by purlins as shown in figure 4.24.

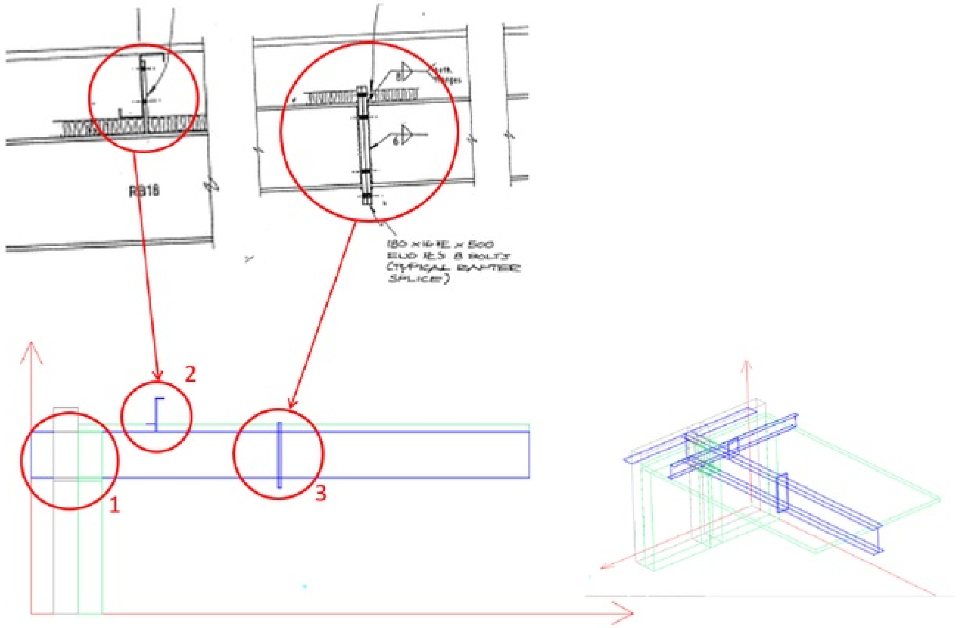


Figure 4.24. Section modelled in Heat3.

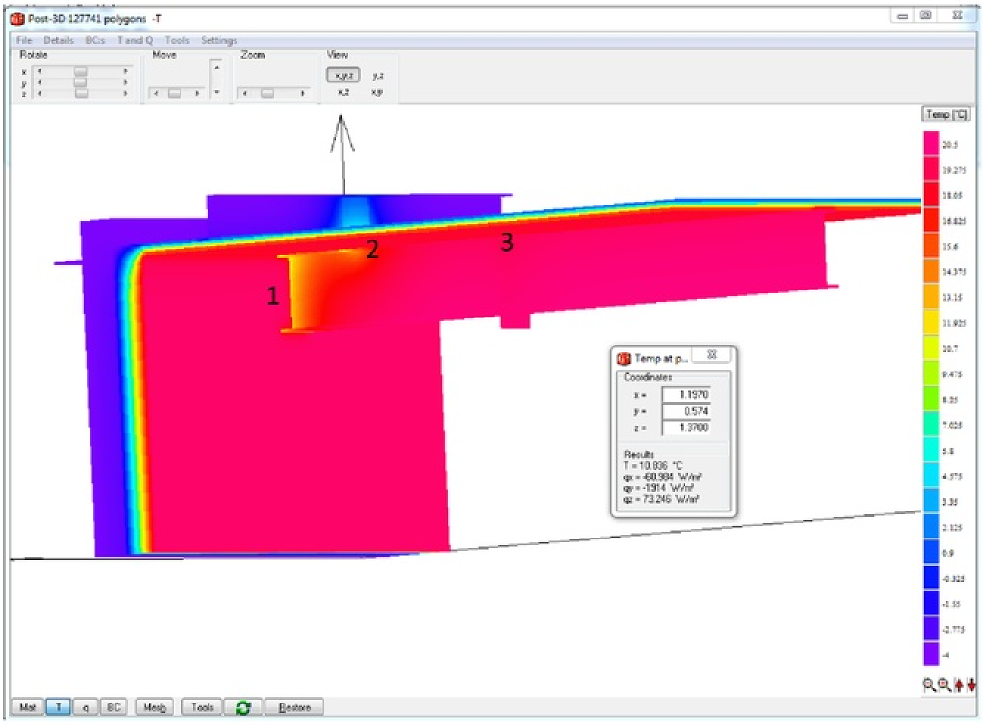


Figure 4.25. Steady thermal analysis generated in Heat3.

The results shown in the steady thermal analysis using Ansys and Heat 3 presents a similar outcome with the purlin surface maximum temperature at 10.371 °C in the Ansys model and 10.336 °C in the Heat3 model. Both surfaces are below the dew point of the design room air, and for this reason any contact of the air with these materials at these particular temperatures will cause condensation. On the other hand, the thermal distribution of the homogeneous section shows a uniform heat dissemination through the insulation layers.

Chapter 5

Discussion

The investigation aimed to predict the causes of condensation. After some visits to the installations and described possible locations of condensation by the personnel, more detailed research took place to study how factors such as temperature and moisture are linked to the causes of condensation. It is of importance to mention that the observation took place during the beginning of spring, and the external temperatures were not close to or below the design conditions of -4 °C. Normal sources of moisture and steam such as bathrooms and people are located in the central section of the building where the offices are, and they do not contribute as a source of latent heat for the overall facility and have been neglected. Also, this section is served by its own air handling unit making this area a different zone to be conditioned.

During inspection of the installations, access to the roof was not approved. The ceiling/ roof configuration is a composite of materials type "sandwich", and there is not a void. For this reason, the physical state of the laminated steel sheets that are exposed to the environment on a daily basis to spot any sign of leakage and infiltration of rain water or accumulation of moisture could not have been determined. However, the NGA department of services indicates that the roof is in a good condition despite more than 25 years of service. In addition, copies of structural and mechanical drawings plans were supplied by the department of services, and it was possible to determine the materials and layout used for the building from them. In the ceiling/roof, one of the layers of insulation is a fibreglass type blanket which was found to be positioned between and over the structural purlins. It is not possible to establish the condition of this layer of insulation through the whole roof as there is no way for it to be assessed, and for this layer of fibre glass to be inspected, it is necessary to dismantle the metallic roof. It is of concern that a precise geometrical cut of these fibreglass blankets to be accommodated between the structural elements of the building was overlooked as it might not be directly in contact with the purlins and structural beams creating pockets of air and reducing insulation of joints. This irregularity might be the cause of air leakage and consequently mould growth within the fibres providing suitable conditions for germination and moisture accumulation.

The material composition of the floor is generic structural concrete slabs, the external walls consist of a two-layer composition of 200 mm precast concrete with an internal layer of 190 mm polystyrene insulation, and the internal walls are made of 190 mm concrete blocks with 190 mm polystyrene insulation facing the conditioned space. Although condensation was not seen in any of the walls within the facility, a brief analysis was made, but it was found that there is no relation between the thermal conductivity in the walls that may affect the ceiling/roof layout and where the interest has been focused.

The ceiling/roof composite is the core of this investigation as this is where condensation has been established. The ceiling/roof construction is a composition of three layers. The internal is 60 mm of polystyrene insulation, approximately 150 mm of fibreglass and a metallic steel zinc coated roof 0.6 mm thick. The purpose of this composition during winter is to maintain the internal design conditions at 22 °C and 55 % relative humidity.

The analysis of temperature relative humidity is straight forward in a building where the construction envelope is of homogenous materials. In order to understand possible factors that affect the conditioned space, it was necessary to analyse the design conditions and equipment that are in charge of maintaining them. The psychrometric analysis and results showed that the HVAC system has been designed to provide air with a constant temperature and relative humidity of 22 °C and 55% respectively. During summer, the AHU provides 19000 L/s into the space, and its configuration is an internal split system; 52 % of the mixed air at 22.6 °C entering the unit is cooled to a temperature of 6.3 °C, and 48% passes through to be mixed with the cooled air, supplying air into the space at 14 °C. During winter, the AHU does not split the flow, and the 1900 L/s are heated from a mixed air temperature of 20.6 °C to a supply air temperature of 28.5 °C. It has been noted that the relative humidity of the supply air during summer is much higher than the design relative humidity, but this factor is due to dryer air conditions during this period of time in comparison to other places in Australia where summer days are highly humid. The results show that the HVAC system under correct functioning provides the required parameters established for conservation within the gallery. However, when measurements of temperature and relative humidity where taken, it was noted that there were temperature fluctuations of -2°C in some internal surfaces with these being more noticeable on the ceiling. These fluctuations would have been bigger and more meaningful if they were taken during the coldest days of winter. However, the values obtained give an indication that the air distribution within the installation is not even around the space; nevertheless, this can be considered a normal condition. The results also allow the design dew point to be identified at 12.6 °C.

Moisture conditions within a controlled spaced are also dictated by the airtightness seal of the envelope in order to control diffusion of water vapour that may create condensation. In any building, it is common to find gaps, cracks and interstitial spaces where water vapour can be displaced, and the magnitude of these might determine the place and quantity of condensation. It was found from inspection that some of the vapour seal tapes utilised where the polystyrene panels meet and where the panels joint structural beams are unattached providing movement of air through these joints. Nonetheless, the movement of air is by exfiltration as the HVAC system has been designed to have 1000 L/s of air for pressurization within the east side of the facility generating a positive pressure difference, and without this vapour tape barrier attached, the probability of condensation increases, especially on windy days when the surface pressure at the roof is negative. Calculations for interstitial condensation show that the saturated vapour pressure values are not bellow the estimated vapour pressure, and for this reason, there is no prediction of condensation between the composite layers within the homogenous arrangement due to vapour diffusion, but there is a minimal possibility of occurrence under the thin layer of metallic roof.

The investigation determined that the ceiling roof materials provide a thermal resistance of 5.51 m^2°C/W which complies with the minimum 3.47 m^2°C/W value of thermal resistance recommended in the Building Code of Australia for the building classification zone and building class specified in section J. Nevertheless, it is important to highlight that the continuous arrangement of these materials is not homogenous throughout the ceiling/roof composition. Some sections of the ceiling/roof where the structural purlins are bolted to the structural beams and roof presents an interruption of the insulation layers and a decrease in thermal resistance to 1.76 m^2°C/W and 0.32 m^2°C/W. The numerical calculations led to predict condensation at these points within the facility.

The thermal analysis in Ansys and HEAT3 of the identified critical points within the structure shows the anticipated condensation predictions based on calculations and exploratory analysis within the facility. It confirms the reliability of the selected insulation materials and their layout, however, the attachment and relationship in the structural configuration forecasts moisture caused by thermal bridging. The purlin surface temperature at 10.371 °C in the Ansys model and 10.336 °C in the Heat3 model is below the dew point of the design room air and for this reason, any contact of the air with the purlins will cause condensation. This surface condensation is more likely to be seen during cold windy days.

Chapter 6

Conclusions and Future Work

Moisture problems are very common in historical buildings such as the NGA off-site facility which was built in the early 90's. The interest of this investigation was to determine the cause of condensation that takes place in the installations and particularly in the roof-ceiling section where the metallic steel roof is fixed to the I-beam by purlins. The most practical and immediate recommended solution is a complete assessment of the vapour seal tape where there is potential of air infiltration to avoid surface condensation. The replacement is necessary where the vapour tape is unattached and where it presents characteristics of deterioration. In addition, it is suggested to box and insulate the structural beams that are visible in the ceiling to avoid thermal bridging as this characteristic has been predicted as a source of condensation.

More complex approaches might be considered to prevent condensation, but they require extensive work and investment to obtain a definite solution. The types of upgrades required might be a new layer of exterior insulation to increase the thermal resistivity in the predicted areas of condensation by using thermal efficient clips and supports. By doing so, the roof needs to be dismantled in order to place a new homogenous insulation layer or underlay and at the same time assess and replace any section of fibreglass insulation where required. The investigation has led to suggest the use of 80 mm expanded polystyrene thermal separators "schock Isokorb" between the steel structures. This type of connector has been developed especially for thermal bridging in the UK and has been thermal modelled by Oxford Brookes University. A brief overview of this device is shown in appendix E.

Another possible option is the addition of a new internal layer of insulated ceiling positioned horizontally across the conditioned space to create a ceiling void that can be mechanically ventilated and controlled. Although this option seems to be unrealistic at this stage due to the complexity that is involved, it is important to be mentioned and can be analysed in more detail for further upgrades. In Australia, airtightness pressurization tests are not mandatory, but it is suggested to carry out one of these tests as the use of coloured gases will give a clear indication of the location and magnitude of this characteristic, especially in a space where the preservation of economic and social valuables is of great importance. Lastly, a more extensive thermal analysis using thermal imaging cameras especially on days where external conditions are adequate for the generation of condensation is also recommended. The thermal imaging project will help to provide a bigger picture of the phenomena and understand any evaporation rate within the structure and materials.

Chapter 7

Abbreviations

AHU – Air Handling Unit

BCA – Building Code of Australia

BMS – Building Management System

BS – British Standards

CIBSE – Chartered Institution of Building Services Engineers

DX – Direct Expansion

IES-VE – Integrated Environmental Solutions-Virtual Environment

HVAC – Heating, Ventilation and Air Conditioning

NGA – National Gallery of Australia

RH – Relative Humidity

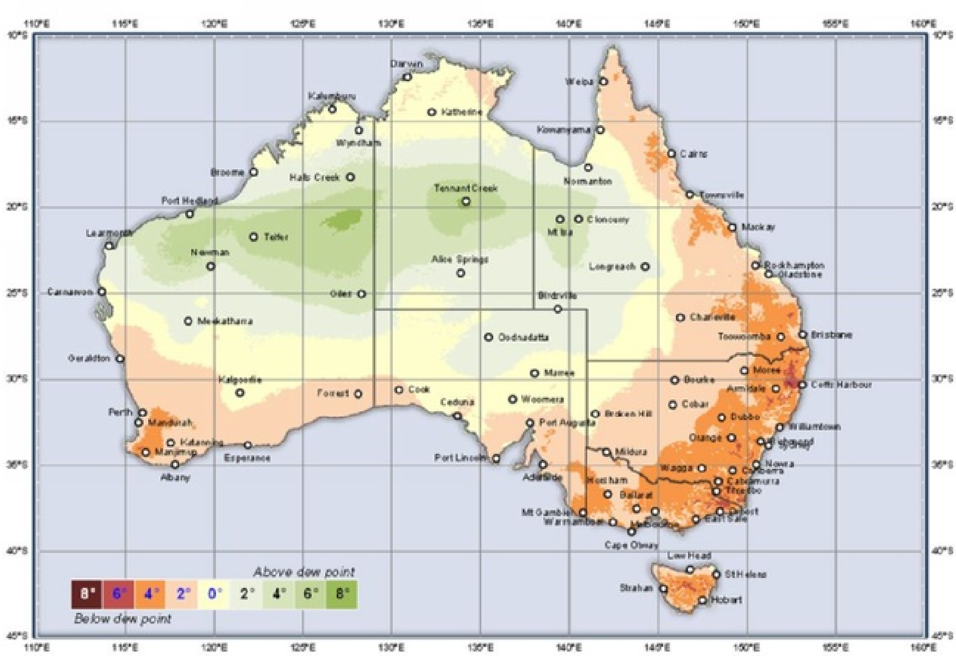
VAV – Variable Air Valve

VPU – Vapour Permeable Underlay

VSD – Variable Speed Drive

Appendix A

Exploratory map of comparative outdoor overnight for potential condensation.

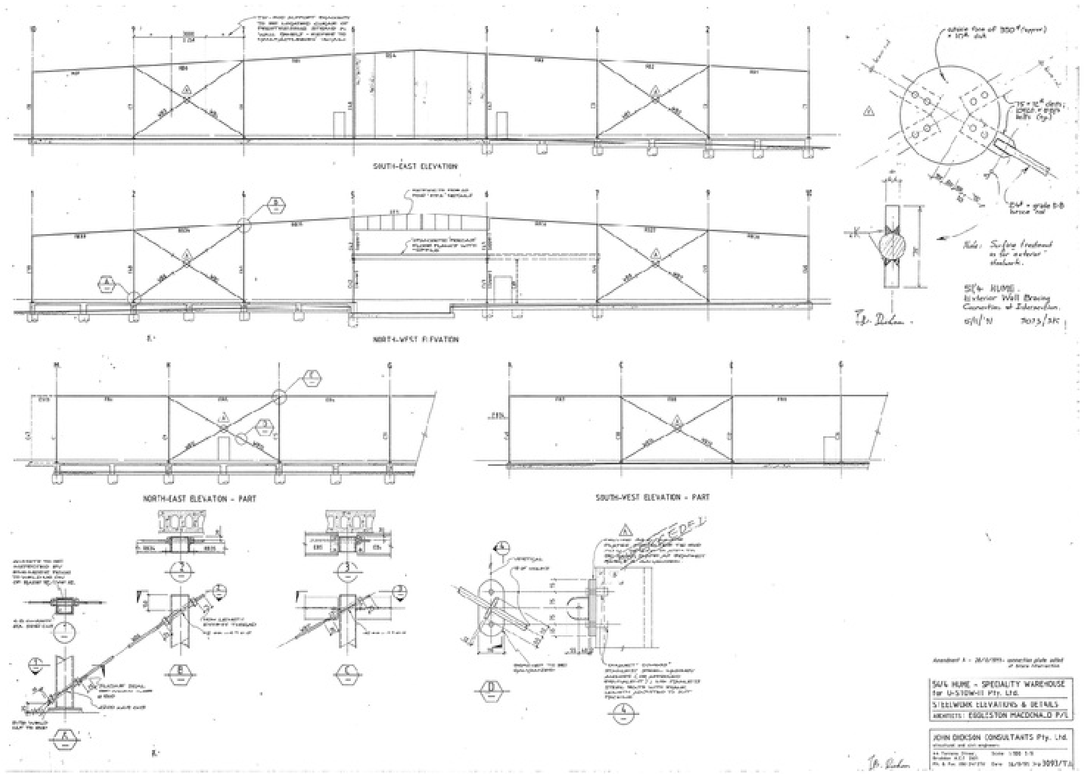


Exploratory map of comparative outdoor overnight for potential condensation [39].

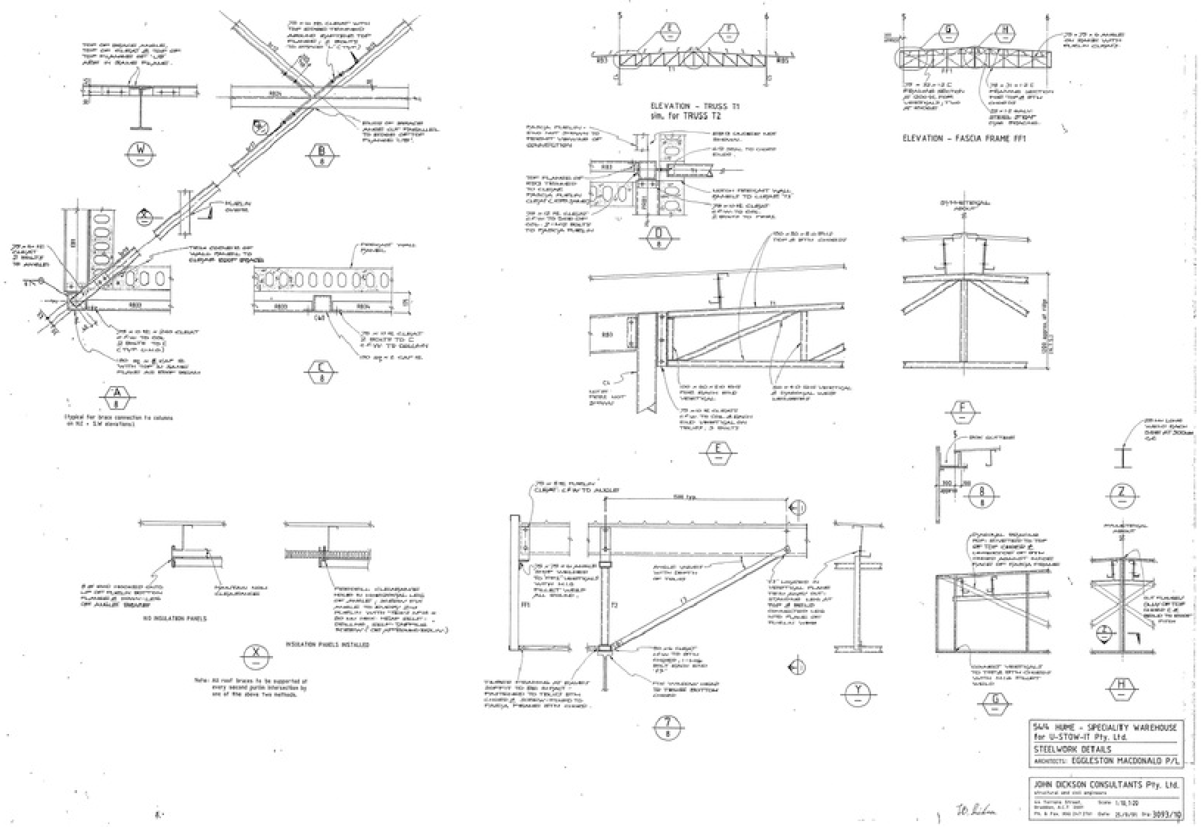
Appendix B

NGA Off-site Facility Floor Plans and Details

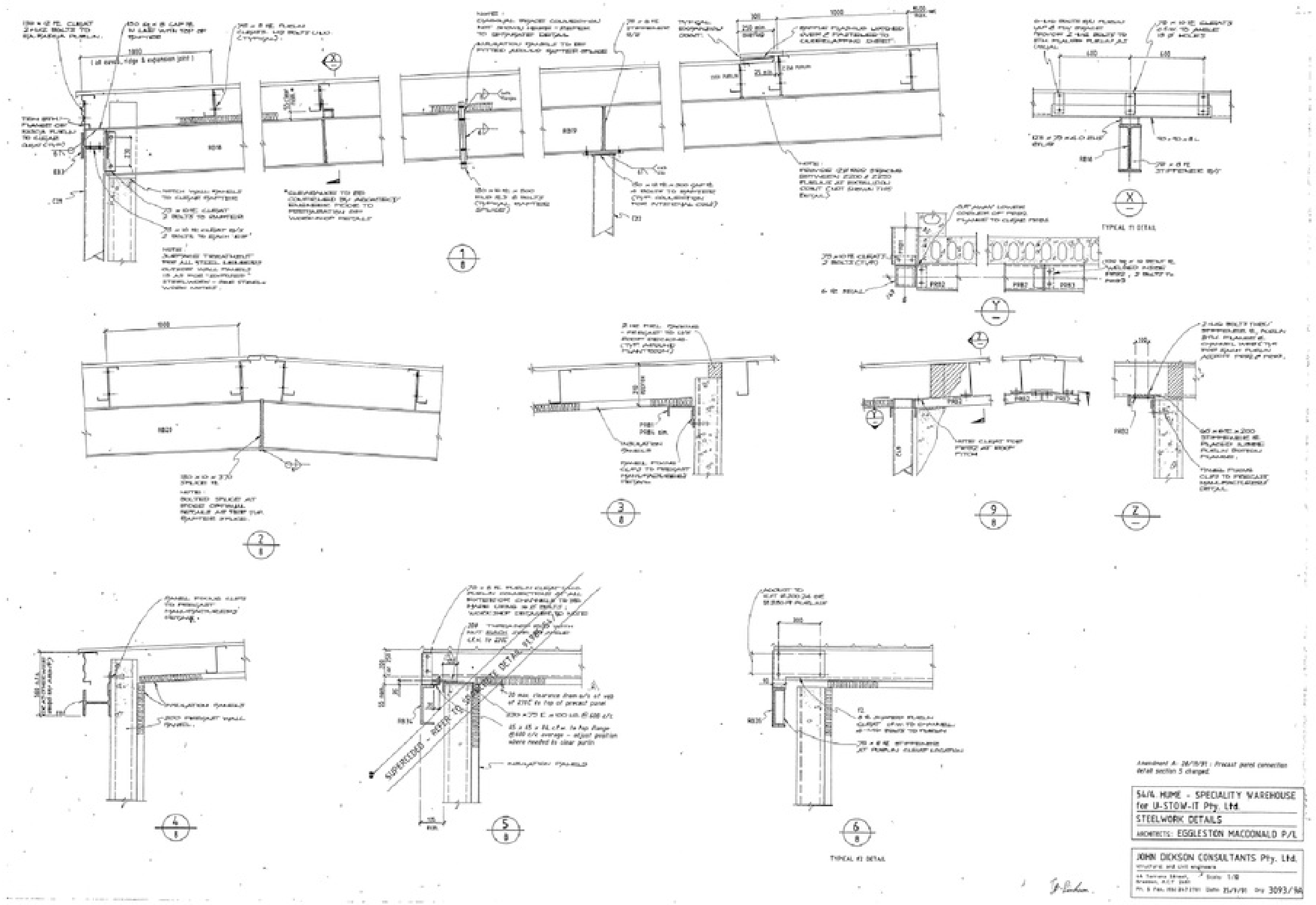
B.1 Steel Work Elevations and Details



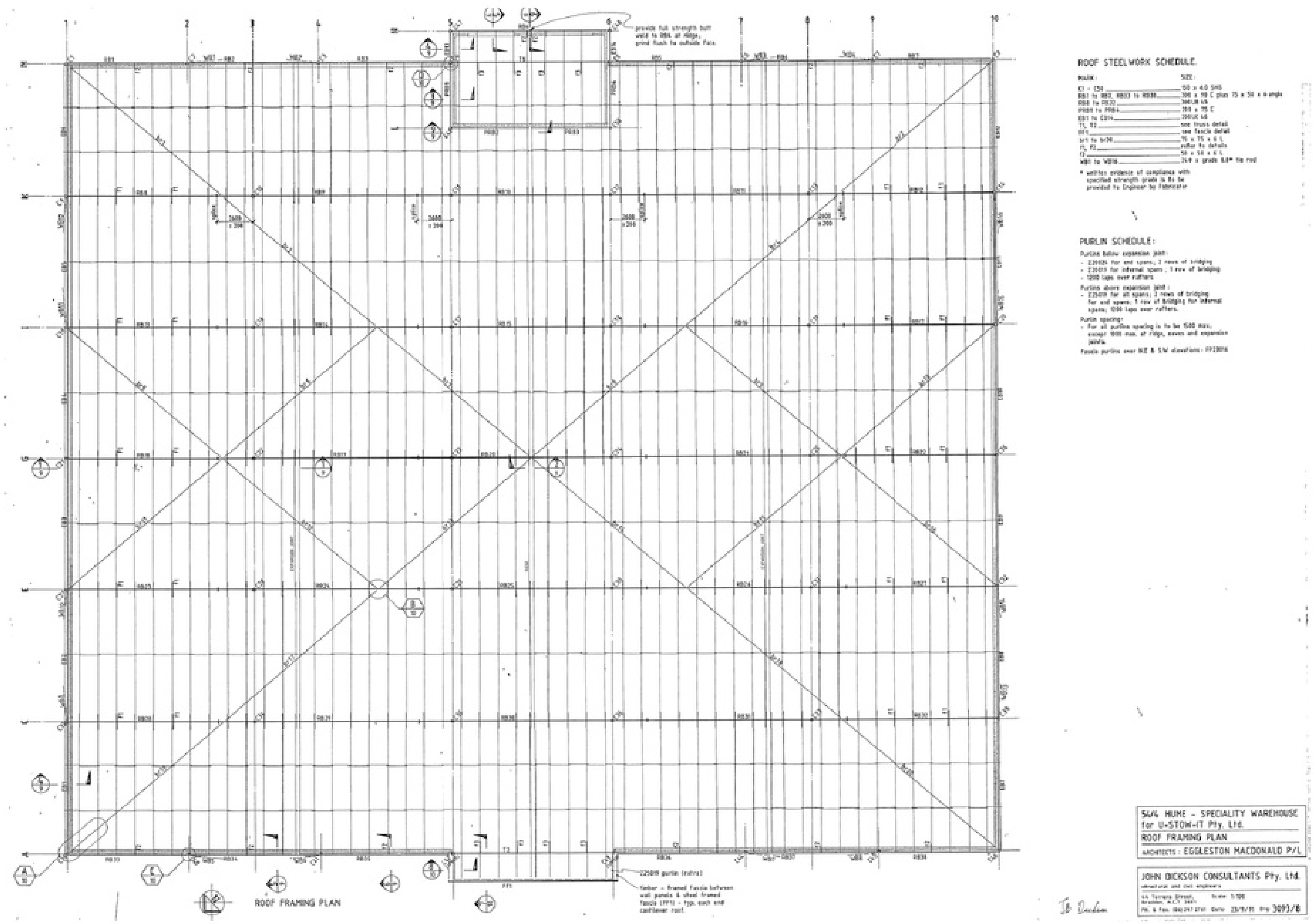
B.2 Steel Work Details



B.3 Steel Work Details



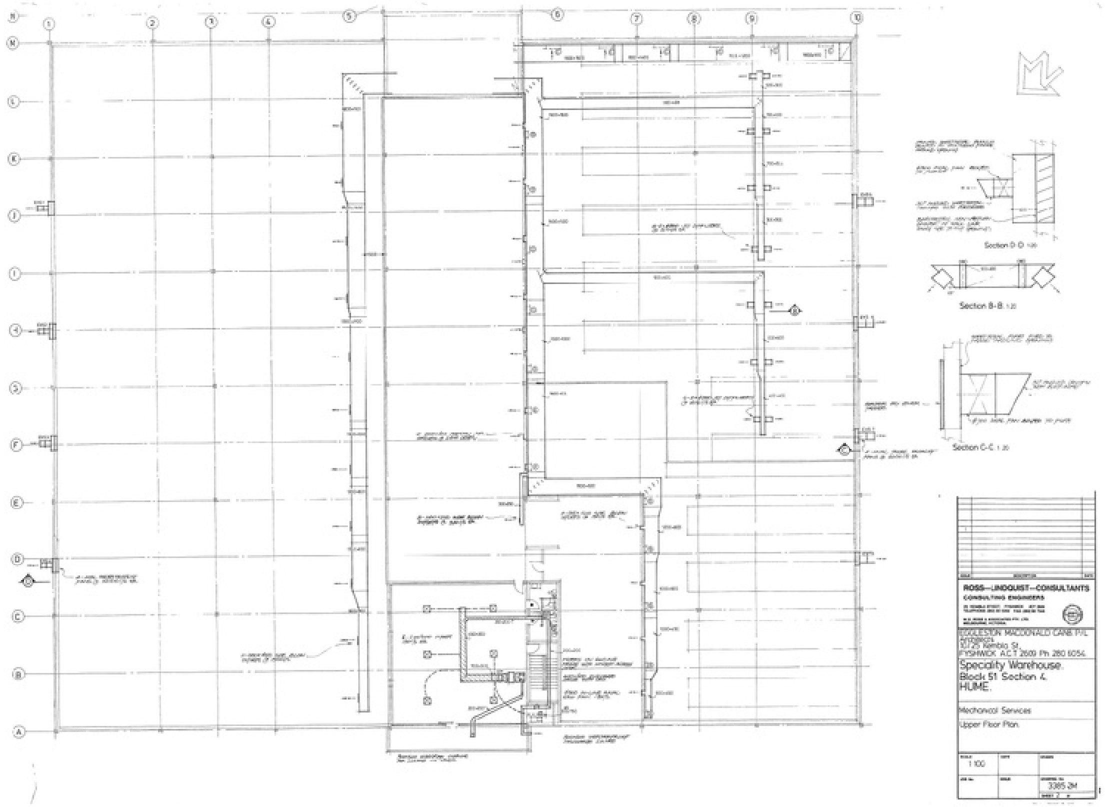
B.4 Roof Framing Plan



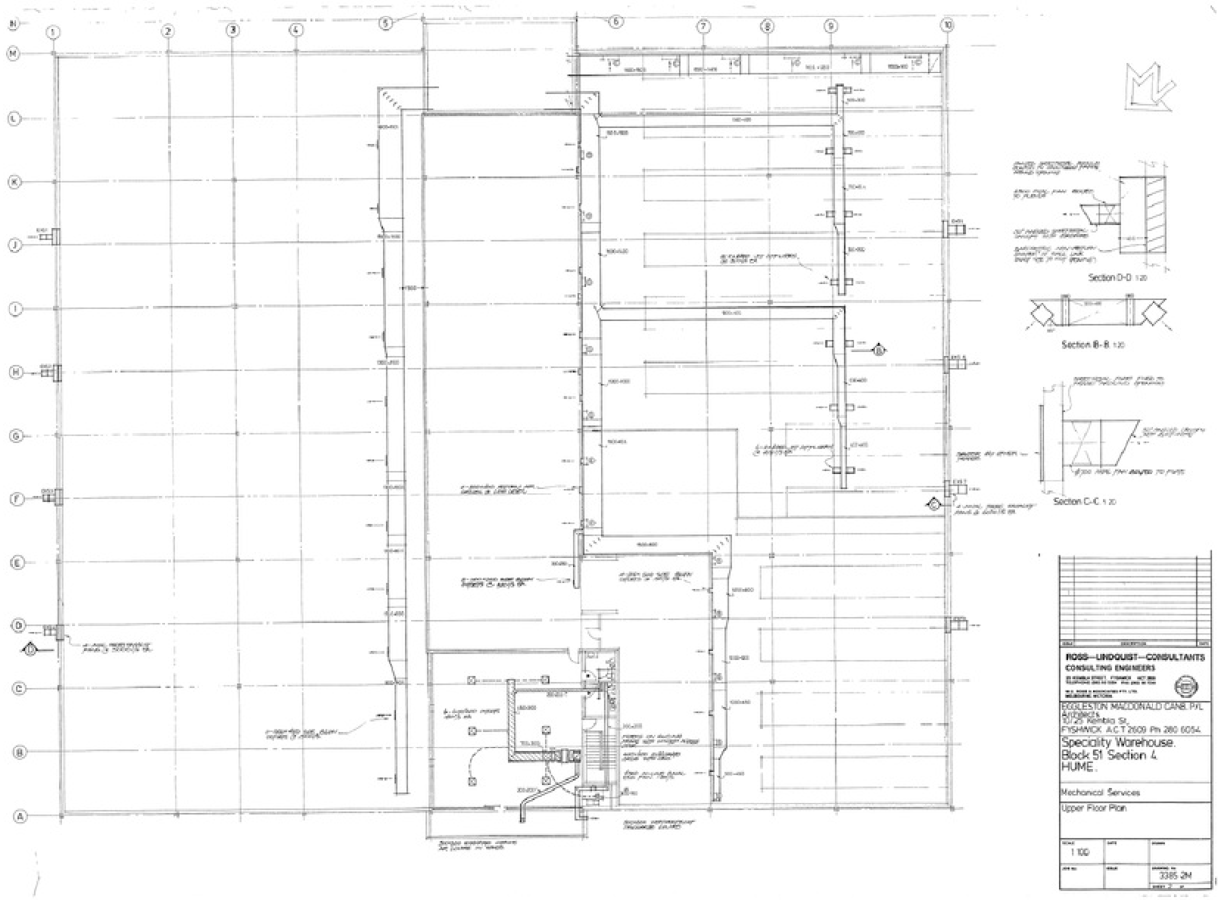
Appendix C

Mechanical Services

C.1 Ventilation Upper Floor



C.2 Ventilation Lower Floor



Appendix D

Schock Isokorb – Structural attachment

Figure D.1. Device and attachment [40].

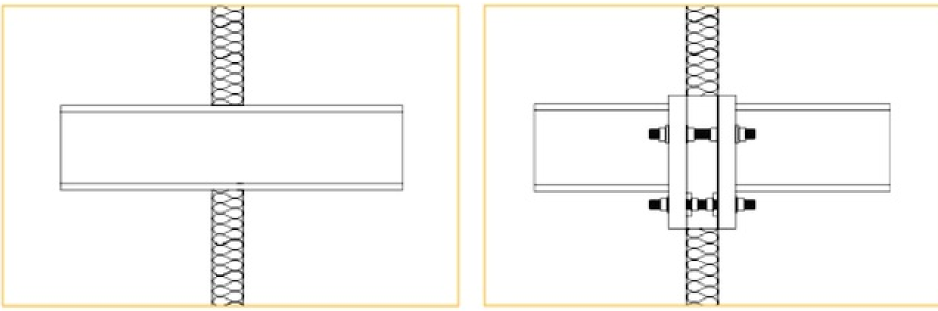


Figure D.2. Structural Attachment [40].

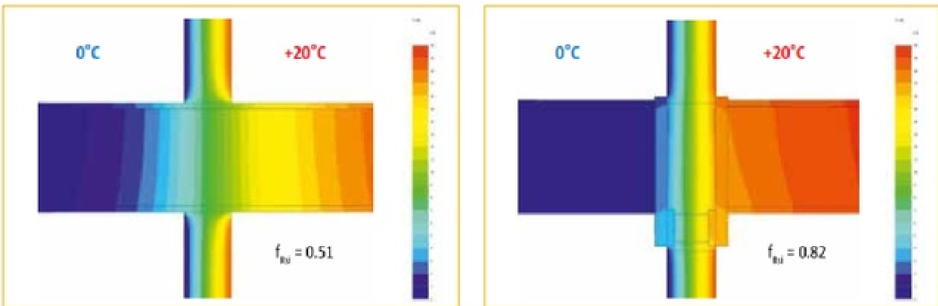


Figure D.3. Thermal analysis without the attachment (left) with attachment (right) [40].

Appendix E

Thermal conductivity of different materials

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Table 6 Thermal Conductivity, Specific Heat Capacity and Density

System Material Database

Material Description	Conductivity (W/mK)	Sp. Heat Capacity (J/kgK)	Density (kg/m3)
Insulating Materials			
Eps Slab	0.035	1400	25
Silicon	0.180	1004	700
Glass-Fibre Quilt	0.040	840	12
Glass-Fibre Slab	0.035	1000	25
Mineral Fibre Slab	0.035	1000	30
Felt & Membrane – Finish – HF-A6	0.415	1088	1249
Mineral Wool/Fibre – Batt – IN01	0.043	837	10
Mineral Wool/Fibre – Fill – IN11	0.046	837	10
Mineral Wool/Fibre – Fill – IN12	0.046	837	11
Cellulose Fill – IN13	0.039	1381	48
Insulation Board – HF-B2	0.043	1381	48
Insulation Board – HF-B5	0.043	837	32
Preformed Mineral Board – IN21	0.042	711	240
Expanded Polystyrene – IN31	0.035	1213	29
Expanded Polyurethane – IN41	0.023	1590	24
Urea Formaldehyde – IN51	0.035	1255	11
Insulation Board Sheathing – IN61	0.055	1297	288
Insulation Board Shingle Backer – IN63	0.058	1297	288
Insulation Board Nail Base Sheathing – IN64	0.064	1297	400
Preformed Roof Insulation – IN71	0.052	837	256
Metal			
Steel	50.000	480	7800
Copper	200.000	418	8900
Aluminium	160.000	896	2800
Lightweight Metallic Cladding	0.290	1000	1250
Steel Siding – HF-A3	44.970	418	7690

Appendix F

Project Meeting Form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	28/07/16	Selection of proposed projects		
2	8/08/16	Revision of Documentation		
3	15/08/16	Request of Access to the installations		
5	30/08/16	Review on theory behind the project		
6	9/09/16	Design Conditions and psychrometrics.		
7	19/09/16	Material Revision		
8	26/09/16	Review on required calculations for scope.		
9	6/10/16	Atmospheric and natural factor to take into account		
10	12/10/16	Structural analysis and Condensation		
11	18/10/16	Analysys obtain with the software		
12	25/10/16	Review of discussion and Conclusions		
13	02/11/16	revision of final report		

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