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Report

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Reduction of Additional (Non-CO2) Greenhouse Gases;
Consequences of using SF6-free sound-proofing glass

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PREFACE

This report presents an analysis of the glass used in The Netherlands, the sound insulation values are therefore expressed in terms of sound insulation values used in The Netherlands. These values are based on the A-weighted sound insulation for a reference sound spectrum $R_{A,V}$ as described in the NEN 5079:1990. Apart from some minor differences, this method corresponds to the single value described in ISO 717-1:1996 using the traffic noise reference spectrum. The results and conclusions of the research presented in this report are based on these reference spectra.

It must be taken into account that the single value sound insulation can also be calculated by the other standardised method in ISO 717-1, the “R_w”-method, which differs from the one used in this report to determine the $R_{A,V}$. (See also chapter 3.1)

Since the “R_w”-method is more sensitive to the higher frequencies, for which SF6 improves the sound insulation, the results of this study are only valid for the method using the traffic noise reference spectrum.

SUMMARY

As part of the programme for the Reduction of Additional Greenhouse Gases undertaken by the Ministry of Housing, Spatial Planning and the Environment (VROM), research is conducted on the consequences of using SF_6-free sound-insulating glass. SF_6 is used in the cavity of double glazing to enhance its sound-insulating quality. As SF_6 contributes to the greenhouse effect, the present report examines weather the use of this gas can be avoided.

The findings presented in this report are based on a study undertaken by Peutz Consulting Engineers. The study focuses on a number of items. First a theoretical explanation of sound wave behaviour in double glazing is provided to gain insight into the sound-insulating effect of double glazing.

Subsequent research deals specifically with the various types of glazing actually being used in practice. On the basis of data derived from standard methods of calculation and data tables, an analysis is made of the composition of different types of glass and their sound-insulating values. These standard methods are frequently used in the field to determine the appropriate type of glazing.

Subsequently, an analysis of the sound insulating properties of more than 100 different types of glazing which are measured in the Peutz's Acoustics Laboratory is performed. The results of these measurements for the various types of glass are compared to the values to be expected on the basis of the standard calculation methods. Based on this comparison, it appears that the frequently-used empirically-based standard calculation models do not adequately predict the actual sound insulation. Actual sound insulation can only be determined accurately by measuring the glass according to the appropriate standards.

On the basis of the glass prices provided by a representative portion of the Dutch glass suppliers, a comparison is made of the prices of gas-filled and air-filled glazing having the same sound-insulating values. Based on this comparison, it appears that no overriding financial consideration motivates the use of SF_6 as a cavity filling. The use of air- or argon-filled cavities is to be preferred to limit greenhouse gas emissions and to increase thermal insulation.

1. INTRODUCTION

An important source of global warming, the greenhouse effect, is the emission of CO_2. In addition to this most important source, other substances contribute to the greenhouse effect. These "additional" greenhouse gases include methane (CH_4), laughing gas (N_2O) and a number of fluoride compounds. Included among these additional greenhouse gases is sulpher-hexafluoride or SF_6. SF_6 is the heaviest greenhouse gas. This gas has several industrial applications and is used in the glass industry to fill the cavities in double-glazing. The good acoustical quality of double glazing having heavy SF_6 gas as a cavity filler are well known, and it is frequently used in areas where a high level of sound insulation is required. Such is particularly the case in locations affected by a great deal of road/railway traffic noise. The prognosis is that the demand for such sound-insulating glass will continue to rise in the future.

In response to the Kyoto protocol, the Ministry of Housing, Spatial Planning and the Environment initiated the Reduction of Additional Greenhouse Gases programme with the aim of limiting emissions of these harmful substances. Besides the well-known "major sources of emission" for these gases, a study conducted by DHV Milieu en Infrastructuur BV [1] provides a survey of emissions from 'small' sources that, up to the present, have not been recognised or quantified in the Netherlands. It reveals that SF_6 is also employed in the Netherlands in the manufacture and use of sound-insulating glass. A significant portion is emitted as leakage during the manufacture of SF_6-filled double glazing (40% of the amount used). During usage, it is assumed that annual leakage into the atmosphere amounts to 1% of the gas stored in the glass cavity.
As part of the Reduction of Additional Greenhouse Gases programme, the Ministry of Housing, Spatial Planning and the Environment initiated, in mid 2001, a project to investigate the ways in which use and emission of this SF_6 source can be reduced. Novem is co-ordinating the execution of this project.

To achieve a reduction in the use of SF_6 in the manufacturing of double glazing and to limit the emissions of this gas from the glass industry, research must be undertaken into alternative forms of glazing having the same sound-insulating quality but no longer involving the use of SF_6. These alternatives must not only have the same sound-insulating quality but also be affordable in terms of their costs. They must furthermore not be the cause of any other environmental problems. This is the only manner in which to stimulate the use of these alternatives on a voluntary basis. It can be expected that significantly more expensive alternatives would not, in fact, be used in the sector unless the laws governing such usage were revised.

1.1. Research Objectives

This report describes the study conducted by Peutz Consulting Engineers under commission from Novem into the alternatives of using SF_6-filled sound-insulating double-glazing. This report on the alternatives and the consequences of not using SF_6 as filler for the cavity in double-glazing can be used to support a policy implemented to combat SF_6 usage in double-glazing. It can function as a technical description of the reasons for using SF_6 and the possible alternatives. This is achieved by a compositional structure that elucidates both theory and data taken from scientific literature, as well as results of laboratory research. The ensuing conclusion will involve a recommendation concerning the feasibility of alternatives with the best price/quality relationship.

1.2. Research Subject Matter

Various tasks are undertaken in this project in order to survey the possibilities involved in the area of double-glazing. As a starting point, it has been decided to review the information available in the scientific literature. This part of the study involves both a theoretical explanation of the influence of gas filling on sound attenuation and an analysis of the experimental results reported in the relevant published studies. The theory is discussed in chapter 2. For a good understanding of subsequent chapters, a reading of the theoretical summary in section 2.2 is, in principle, sufficient.

Following this theoretical discussion, there is an analysis of the laboratory tests of various types and combinations of glazing and gas fillings conducted in the Peutz's Acoustics Laboratory . This extensive set of measurements is especially interesting because it involves measurements made under identical conditions in the identical laboratory. By this means, a high level of accuracy was achieved and an ideal set of results was obtained in order to compare the sound-insulating capacities of double-glazing with diverse gas fillings.

After this scientific analysis, a cost analysis is conducted in order to select the types of glass that have a good price/quality relationship, so that they can be discussed further. On this basis, an overview will be presented of the relevant SF_6 glazing and the possible SF_6-free alternatives.

2. THEORY

2.1. Introduction

To gain a good insight into the effect of sound-insulating double-glazing, this chapter will provide a theoretical explanation of the interaction of sound waves with double-glazing. The influence of variables as mass and cavity width on the sound insulation can be derived from this theory. Studying this theoretical information can provide an explanation for the various physical phenomena determining the sound insulation provided by double-glazing. This technical explanation can be a benefit for those who are interested in the background underlying the behaviour of sound-insulating double-glazing. A thorough examination of the theory in this chapter is, however, not essential for understanding the rest of the report. The intention is to provide an overview of the relationship between the various parameters of double glazing and sound insulation; the complex theoretical derivation of these relationships falls outside the scope of this report. We encourage those interested in such information to consult the available literature on the subject. A summary and conclusion of all that is discussed in this chapter (sections 2.3–2.8) can be found in 2.2. This can be read independently of the remaining parts of the chapter.

2.2. Summary and conclusions of chapter 2

The sensitivity of the human ear is dependent on the frequency of the sound that encounters it. The sensitivity increases with frequency until 2000 Hz, beyond which sensitivity decreases as frequency increases.

The sound insulation provided by double-glazing also depends on the frequency of the sound that encounters it. The frequency dependent nature of sound insulation is indicated by a sound-insulation curve, such as the one shown in figure 2.1, which shows that glass is a better insulator at higher frequencies. As figure 2.1 also indicates, the sound-insulation curve can be divided into four distinct ranges, each of which is characterised by a different physical phenomenon. These phenomena will now be briefly explained.

Range 1 is the stiffness range, where the sound insulation can be described in terms of the theoretical mass law. In this range the cavity filling connects the two glass panels because of the stiffness of the filling, therefore the sound insulation of the two plates is comparable to the sound insulation of a single plate with the same mass. This low frequency range is mostly of no interest because of the diminishing sensitivity of the human ear to low frequencies. In this range, sound insulation increases at a rate of 6 dB per octave.

With increasing frequency, we arrive at range II: the resonance range. Here, the curve no longer follows the mass law, as it did in range I, but decreases sharply to a minimum level at resonance frequency f_0. A sound wave that encounters double-glazing causes the encountered plate to vibrate. This plate is then, via the air layer that functions as a spring, connected to the other glass plate. At a certain sound-wave frequency, the system will start to resonance. The air spring then readily conducts the vibration of one plate to the other and, at this resonance frequency, sound attenuation is consequently minimal. Such is shown by the resonance curve in range II.

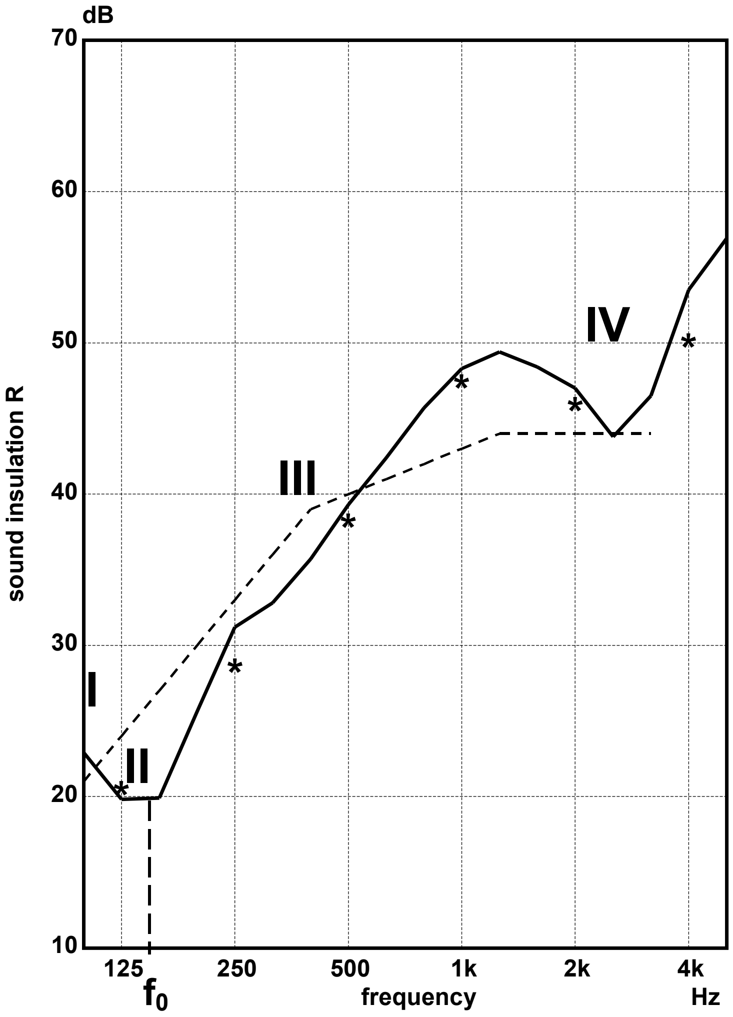

Figure 2.1: Example of a sound-insulation curve for double-glazing. The solid line connects measurement data from various octave bands; the dotted line is the curve of reference values as defined in ISO 717-1:1996; I) Stiffness range; II) Resonance range; III) Mass range; IV) Coincidence range

Above the resonance range comes the mass range, in this frequency range the intervening air layer no longer couples the motion of the two masses. The plates move separately and the sound insulation increases with increasing mass. In this range the sound insulation will rise sharply as the frequency increases (range III). This shows the importance of the resonance frequency. Since the sound insulation increases sharply above this frequency, a lower f_0 frequency means that this increase can begin sooner and the sound insulation curve become higher in the frequency range of interest. The resonance frequency given in equation 2.1 indicates that an increase in glass mass and/or cavity width decreases the resonance frequency. By this means, it is possible to achieve a higher level of sound insulation in the mid frequency range.

In frequency range IV, the question of coincidence arises. Coincidence occurs when the wavelength of the incident sound wave coincides with the free wave of the glass. The free wave is a movement that a plate makes when it receives an initial strike (comparable to the wave pattern generated by a pebble thrown into a pond). When the wavelength of the air-transmitted sound wave that encounters the plate accords with the wavelength of the free wave in the glass plate, the sound wave meets less resistance and is, consequently, attenuated to a lesser extent. This results in a greater transmission of sound through the glass. The combination of frequency and incident angle determines if a sound wave coincides with the material's free wave. When the incident beam is non-directional (from all angles) coincidence occurs in a wider range of frequencies. This explains the decreasing sound insulation effect in range IV of the insulation curve.

The coincidence range in the insulation curve can be determinative of the sound insulation performance of double-glazing. Using laminated glass can, however, reduce the coincidence phenomenon.

SF_6 gas can be used as cavity filling for double-glazing. This heavy gas has the effect, on the one hand, of reducing sound insulation in the resonance range II (the dip is narrower and deeper) and, on the other, of increasing sound insulation in the mid frequency range III. The movement of the plates in relation to the cavity is altered because the cavity has become filled with a heavier gas. Consequently, the movement of the mass-spring system has a positive effect on the sound insulation.

2.3. Double glazing with air-filled cavity

The double glazing system consists of two sheets of glass separated by a cavity [2]; see figure 2.2. The wall mass per unit surface area [kg/m^2] for plate 1 and 2 are respectively m_1 and m_2, the width of the cavity is h. These factors are also the main variables in the system; it is also possible to use air instead of another gas (argon or SF_6) as the cavity filling. Additionally, laminated glass sheets can be used instead of homogeneous glass plates. Laminated glass means that one of the two sheets of glass is composed of two (or more) glass layers joined together by a layer of resin, a plastic film or a thin air layer. This is done in order to avoid the so-called coincidence effects, a matter further discussed in section 2.5. In the following discussion, we deal with non-laminated glass and air as cavity filling. In section 2.6, some consideration will be given to laminated glass, and in section 2.8, the influence of gas filling on sound insulation will be explained.

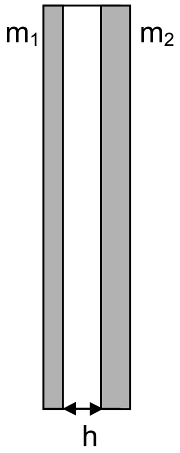

Figure 2.2: Double-glazing system with an air-filled cavity

A sound wave encountering the system from the left will cause motion in plate 1. The motion of plate 1 will cause the gas in the cavity to move, and this will, in turn, produce motion in plate 2. The motion of plate 2 causes a sound wave in the space on the right of the construction. The intensity of the transmitted sound should, in a well-insulated construction, be much smaller than the incident pressure wave.

The mathematical model for such a system is based on a dynamic equilibrium between the two glass panels linked by a spring system (the filled cavity acting here as the spring system). The manner in which this mass-spring system behaves is dependent on the frequency of the sound wave that enters the system. The sound-insulation measurements are therefore always taken over the whole range of frequencies. In the sound-insulation spectrum, the sound insulation is plotted for the complete frequency range.
When such a double construction is caused to vibrate, effects such as resonance and coincidence are brought into play. These effects are recognisable in the sound-insulation spectrum. At various frequencies, effects occur that may be beneficial or detrimental for sound insulation. These various phenomena in the sound-insulation curve will be discussed below. Given an awareness of these phenomena, it is possible to analyse and explain different ranges in the spectrum.

2.4. Mass-spring resonance

We begin by presupposing that a double glazing element is caused to vibrate by a sound wave that encounters the glass at a perpendicular angle. As already mentioned, this occurrence can be modelled as a mass-spring system in which the air layer acts as an air-spring that has a certain resistance. Because of the dynamic equilibrium between the two glass plates and the air filling, this mass-spring system will start resonating at a specific frequency. This frequency at which the glass panels resonate against the air

spring is the mass-spring resonance frequency f_0. The frequency of the incident sound corresponds to the vibration of the system itself if it was in free vibration.
With such cavity constructions as double-glazing, this resonance has a great influence on the sound attenuation. The sound wave is largely transmitted and the sound insulation very limited at this frequency. This resonance frequency is described by the following equation in which the masses of the walls and the width of the cavity function as variables.

$$\omega_0 = \sqrt{\frac{\rho c^2}{h}\left[\frac{1}{m_1} + \frac{1}{m_2}\right]} \tag{2.1}$$

Where:
m_1 = mass of wall 1 per unit surface area [kg/m^2],
m_2 = mass of wall 2 per unit surface area [kg/m^2],
h = width of the cavity [m].
c = the velocity of sound in air [m/s].
ρ = the density of the air [kg/m^3]
In the above equation, the resonance frequency is calculated for a sound wave that encounters the wall at an angle perpendicular to the wall. The following relation holds for the frequency: $\omega=2\pi f$. As the sound wave encounters the wall at a smaller angle, the resonance frequency must be adjusted by a factor of $1/\cos\theta$. The effect of non-directional incident sound (sound from all angles) can be determined by assuming an averaged incident angle of 45° and by calculating the resonance frequency on that basis.

The mass-spring resonance frequency f_0 divides the total range of frequencies into three (sub)ranges. The sound insulation differs in each of the ranges $f \ll f_0$, $f=f_0$ and $f \gg f_0$. Figure 2.1 displays an example of a measured sound-insulation curve for a type of double-glazing. Range I, in which $f \ll f_0$, is the stiffness range, range II the resonance range and range III the mass range. The decrease in sound-insulation in range IV is associated with coincidence and will be discussed in section 2.5.

The sound insulation R in range I (see figure 2.1) can be approximated by the sound insulation of a single wall construction, the so-called theoretical mass law. For the derivation of the theory of the mass law for single walls, we refer to the literature on this subject. The theoretical mass law for a single wall with mass m is given in the following equation:

$$R = 20\log\frac{\omega m}{2\rho c} \tag{2.2}$$

To apply this relation to a double wall system in this frequency range, the total mass of the two walls must be entered: $m=m_1+m_2$. This formula indicates that sound attenuation increases at a rate of 6 dB per octave (when the frequency is doubled) and 6 dB when the mass is doubled.

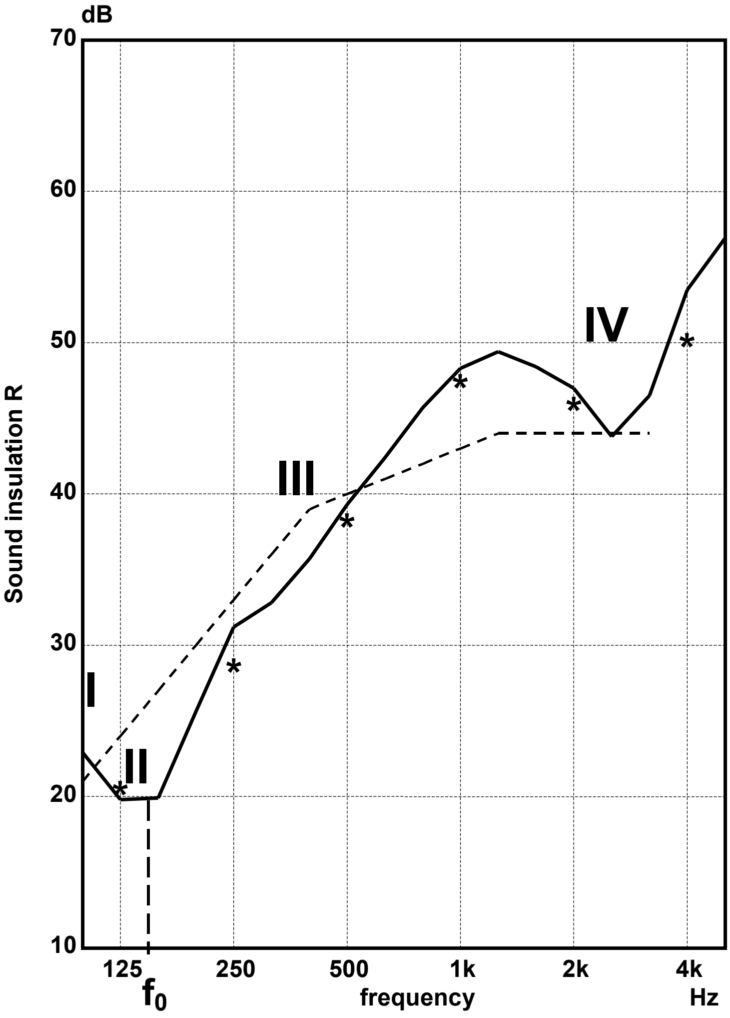

Figure 2.1*(again)*: Example of a sound-insulation curve for double glazing. The solid line connects measurement data for various octave bands; the dotted line is the curve of reference values as defined in ISO 717-1:1996; I) Stiffness range; II) Resonance range; iii) Mass range; IV) Coincidence range

When $f=f_0$, the sound insulation is minimal. The resulting dip in the insulation curve at f_0 is clearly visible in figure 2.1. Above the resonance frequency, the sound-insulation increases up to the coincidence range (IV). For range III, sound insulation can be modelled as follows:

$$R = 20\log\frac{\omega m_1}{2\rho c} + 20\log\frac{\omega m_2}{2\rho c} + 20\log\frac{2\omega h}{c} \qquad (2.3)$$

This equation clearly demonstrates how the sound insulation of double glazing conforms to the sound insulation that would be produced by a single glass plate with a mass of $m=m_1+m_2$. A sound-insulating construction consisting of a single wall with mass m_1+m_2 can be compared to the sound insulation of a double wall with mass m_1 and mass m_2. In the first case, the mass law stated in equation 2.2 is valid for the global mass m_1+m_2. In the case involving two plates, sound attenuation occurs in the manner formulated by equation 2.3. This produces in this range a sound insulation of 18 dB per octave for a double wall assembly, as compared to 6 dB per octave in the case of a single wall. For this reason, a double wall provides greater sound insulation than a single wall of equal mass.

The position of the mass-spring resonance frequency has, in this manner, an effect on the slope of the insulation curve. The lower that f_0 is the sooner that the sound-insulation curve begins to rise which results in an improved sound insulation in the significant frequency range, as stated in equation 2.3.
If the resonance frequency lies in the frequency range of interest, efforts must be made to minimise as much as possible the reduced insulation effect at this frequency. This means limiting the "dip" in the curve at f_0.
The position of the resonance frequency is determined by equation 2.1. Increasing the mass lowers the resonance frequency, resulting in an increase of sound insulation starting at lower frequencies.. This will produce a higher level of sound insulation in range III. A larger cavity width has the same effect of providing enhanced sound insulation performance.

In practice, formula 2.3 therefore implies that sound insulation can be improved by increasing the mass of the glass plates (thicker glass plates) and by enlarging the width of the cavity. The use of thicker glass would lead directly to more expensive glass plates. Enlargement of the cavity could, to a certain extent, produce improved performance at (very) little additional cost.

2.5. Coincidence

When a pulse encounters a single plate, the impact will produce a free bending wave in this plate, comparable to the effect of a pebble thrown into water. This wave is initiated by the initial strike; the resulting vibration is a property of the plate itself and is determined by such material traits as stiffness in flexure, elasticity, thickness and mass. This wave, which results from a stimulus but whose propagation is only governed by the properties of the material itself, is called a *free* bending wave. The propagation velocity of this wave is c_{free}.
In the case of a plane wave contacting the plate at a certain angle, a pattern of over- and underpressures occurs on the plate. This forces the plate into a certain shape, and this deformation, by accompanying the sound wave, propagates through the plate. The propagation velocity of this wave is c_{forced}. In this situation, the sound wave will force the plate to vibrate in the same way as the sound waveform itself. The plate is, as it were, forced to move along with the sound wave. This principle is what we name a *forced* wave. This wave system is fully determined by the incident sound wave and is independent of the properties of the plate.

An incident sound wave simultaneously generates two wave systems in the plate: the free vibration that the plate wants to execute and the forced vibration imposed on it by the sound wave. When a sound wave encounters a plate, there is always a certain frequency where the wavelengths of the forced wave and the material's free wave coincide. At this frequency, the wave imposed on the system corresponds to the system's own free bending wave. This results in an strong vibration in the plate and therefore a strong radiation of sound. Geometrically, the phenomenon implies that the path of the incident wave coincides with the path of the free bending wave. The wave velocity $c_{forced} = c_{free}$. The occurrence of such effect is called coincidence. Theoretically, the wave is freely transmitted, and there is at this frequency very little sound attenuation. The frequency at which the coincidence phenomenon occurs depends on the angle of the incident sound wave. At different angles, the incident sound waves coincide with the free bending wave at different frequencies. For a multidirectional incident wave encountering a single plate, coincidence will appear at a wide range of frequencies. The lowest frequency at which coincidence occurs is identified as the critical frequency f_c, which is given in the following equation:

$$f_c \cdot d = \frac{c^2}{2\pi}\sqrt{\frac{12\rho}{E}} \qquad (2.4)$$

where ρ is the density and d the thickness of the wall, and E the elasticity modulus (N/m^3) of the glass. The product of the critical frequency and the thickness of the glass is therefore a constant. This constant is determined by the material properties.

Coincidence also occurs in double-glazing, as its sound insulation is also reduced as a result of the coincidence of free and forced waves. However, the derivation of the precise manners in which such waves coincide in double-glazing will lead us outside of the scope of this report. In this case the wave numbers of plate 1 and 2 determine the coincidence of the total construction. Both plates have their own free bending waves. The degree of coincidence depends on the properties of the plates. If they are of identical thickness, then they also share the same critical frequency and the coincidence effect is, in such cases, stronger than it is for a single leaf structure. In practice, plates of unequal thickness are used in order to attain higher levels of insulation. The decreased effectiveness of the insulation provided by plate 1 at the critical frequency is then compensated by the sound insulation of the second plate.

The sound insulation performance of double-glazing will markedly deteriorate once the critical frequency is surpassed. This frequency is most commonly on the order of 2000–3000 Hz. The coincidence range is shown in figure 2.1 as range IV. In practice, this can be heard as a distinct sizzling, especially at slanting angles of incidence (such as those occurring to apartments on the top floors of high-rise buildings). Often, this range has a relatively limited effect on the sound insulation value needed for road traffic, such as that which will be discussed in section 3.2.

2.6. Laminated glass

To avoid the above-mentioned coincidence problem in double-glazing, double glazing constructions can use, instead of homogeneous plates, plates having an elastic intermediate layer. In such a construction, one of the two glass plates is composed of two thinner plates separated by an elastic intermediate layer. This could be one or more layers of PVB film, a layer of acrylic resin or an air layer.

By using an intermediate layer, the motion of the glass plate is altered. The two glass plates joined by the intermediate layer do not move as a single plate. The plate assembly moves as two joined plates each having half of their combined thickness and no longer as a single plate with thickness h. This reduction in thickness displaces the critical frequency to a higher level (see equation 2.4). Furthermore, the coincidence effect is reduced by the fact that the intermediate layer damps the movements of the plates.

The result is therefore twofold: the critical frequency is raised causing the coincidence range also to be displaced to higher frequencies, and the effect of coincidence on the sound insulation is reduced by the damping of the elastic intermediate layer. The extent in which the sound insulation is improved when laminated glass is used, compared to non-laminated glass, depends on which intermediate layer is used.

- Using a PVB film as the elastic intermediate layer will lead to a smaller reduction in sound insulation in the coincidence range compared to (non-laminated) glass. Sound insulation in range IV will be higher. Improvements in this range can cause a significant improved performance in sound insulation as a whole.

- If acrylic resin is used, the coincidence phenomenon is displaced to higher frequencies. In addition, a reduction of the phenomenon occurs causing it to be less clearly discernible, or even entirely eliminated. The insulation effect at lower frequencies also increases somewhat.
- Even a thin air layer can be used as an elastic intermediate layer. This also causes the coincidence phenomenon to be displaced to higher frequencies. There is also a positive effect on sound insulation, although more limited that it is when acrylic resin is used.

2.7. Effect of resonance and coincidence on the insulation curve.

Now that resonance and coincidence have been discussed, these effects can be combined to obtain a complete overview of the insulation curve presented in figure 2.1. In the description of the mass-spring resonance in section 2.4, the total frequency range was divided into (sub)ranges I, II, III and IV. In the stiffness range I, mass law (formula 2.2) is applicable; in the resonance range II, sound insulation is reduced. In the mass range III, equation 2.3 is applicable and, theoretically, a sound insulation effect amounting to 18 dB per octave is produced. The coincidence effect appears in range IV and causes sound insulation performance to deteriorate in that region. This reduction can possibly be limited by using laminated glass.

In practice, these different ranges can often be readily distinguished when measuring insulation curves. It is therefore possible, on the basis of the insulation curve, to determine where weaknesses are located. This tool can be used to determine the possibilities of improving the sound insulation performance of glass products. The example in figure 2.1 is an insulation curve for an assembly in which both plates are laminated. The dotted line is a reference contour used to calculate the R_w values conforming to ISO 717-1:1996. More will be said about this curve in section 3.2.

2.8. Effect of gas filling on sound insulation

Until this point, it has been assumed that we are dealing with air-filled double-glazing. Using a heavier gas to fill the cavity alters the sound insulation quality of the glazing. A cavity filled with a heavier gas results in improved sound insulation in the mid frequency range (400–1400 Hz). Conversely, there is a reduced sound insulation effect in the resonance range. The influence of heavy gas on sound insulation can be explained in terms of the influence that the stiffness of the gas has on the mass-spring motion [3].

The stiffness of a cavity filling can be compared to a spring constant in a mass-spring system. With slanting incident sound, stiffness increases. When incident sound encounters the plate from a certain angle the dynamic equilibrium is determined by the wave components perpendicular to the plate. The stiffness of the cavity is therefore dependent on the angle of incidence, and this stiffness increases as the angle becomes larger. The stiffness *s* is given is given by the following equation:

$$s = s(\theta) = s_0 \cdot \frac{1}{1 - \left(\frac{c_G}{c_L}\right)^2 \sin^2\theta} \tag{2.5}$$

along with:

$$s_0 = \frac{\rho_G \cdot c_G^2}{h} \tag{2.6}$$

Where:

θ = angle of incidence

c_G = velocity of sound in the gas filler

c_A = velocity of sound in air

ρ_G = density of the gas

The variable s_0 is almost independent of the gas: as density increases, the velocity of sound decreases. The denominator in 2.5 defines the dependence of the stiffness on the angle of incidence. Equation 2.5 shows that for perpendicular incidence, $s(\theta) = s_0$. The stiffness variable s_0 for θ=0º can be directly derived from the mass-spring resonance frequency (eq. 2.1). For slanting angles of incidence, stiffness increases along with the angle of incidence. Slanting incident waves are consequently better transmitted. Comparing the extent to which the stiffness properties of air and heavy gas depend on the angle of incidence, equation 2.5 makes it clear that this dependence is smaller for heavy gas than it is for air. This discrepancy is indicated by the factor $(c_G/c_L)^2$ in front of the angle-dependence term. The stiffness resulting from multidirectional incident sound will be lower in the case of a heavy gas than it would be for air.

The mass-spring motion of the glass plates and gas layer is governed by the stiffness of the cavity gas. Since the stiffness of this gas is dependent on the angle of incidence, the mass-spring resonance is also dependent on this angle, as follows:

$$\omega_0(\theta) = \sqrt{s(\theta) \cdot \left(\frac{1}{m_1} + \frac{1}{m_2}\right)} \tag{2.7}$$

As the stiffness of, in this case, SF_6 is to a lesser degree angle-dependent than that of an air-filling, the resonance frequency is, in the case of a heavy gas, also less dependent on the angle of incidence. The resonance frequencies for diverse angles will remain close to each other, with the result that there is a narrow resonance dip for multidirectional incident sound. In the case of an air-filled cavity, the resonance frequency will be more strongly dependent on the angle of incidence. The effect of various angles of incidence will produce a broader resonance dip in air-filled double-glazing, as the individual resonance frequencies are more widespread. The resonance of heavy-gas-filled double-glazing will therefore result in a lower mass-spring resonance frequency than an air-filled system. Additionally, the reduction in sound insulation at this resonance frequency will be deeper because the frequencies generated at various angles are more concentrated.

Moreover, it follows that the effectiveness of the sound insulation above the resonance frequency of multidirectional incident sound begins to increase sooner for heavy-gas-filled assemblies than it does for air-filled ones. This factor provides the basis for the improved sound insulation performance in the mid frequency range when SF_6 is used. The influence of heavy gas filling on insulation can be explained by referring to what happens in the resonance range and approximately 2 octaves above it. At higher frequencies, other effects (especially coincidence) have a role to play, and they cannot be sufficiently clarified by the theory outlined in this chapter.

The improvement in insulation is, therefore, dependent on the velocity of sound in the cavity gas. A heavier gas with a lower velocity of sound provides an improved sound insulation performance. The achievable improvements are, however, limited. A gas heavier than SF_6 does not appear to provide any additional benefit. The velocity of sound in air is 340 m/s; in SF_6, it is 149 m/s. A cavity filled with a still heavier gas, such as C_4F_8, having a lower velocity of sound (e.g. 107 m/s for C_4F_8) does not provide any improvement in sound insulation. Moreover, it should be noted that C_4F_8 is also a greenhouse gas and can therefore not be considered as an alternative to SF_6. Filling the cavity with argon, a gas that is indeed heavier than air, does not have a significant effect on sound insulation, although it does provide better thermal insulation.

In sum, it can be stated that SF_6-filled double glazing produces the following differences when compared with an air-filled construction. These differences are based on empirical data.

- The mass-spring resonance f_0 occurs at a lower frequency than it does with air filling. The resonance dip is deeper than it is with an air-filled cavity.
- In the range above the resonance frequency, insulation performance increases more strongly than with air-filling. This increase is also dependent on the composition of the gas: a higher percentage of SF_6 provides a more enhanced sound insulation. Empirical methods of calculation [4.5] are used to determine sound insulation performance.
- At higher frequencies, there are no apparent differences between the various types of glazing. SF_6 has consequently no effect on insulation in the range around and above the critical frequency. At the critical frequency, the insulation curve of heavy-gas-filled glazing joins up with the sound insulation curve of air-filled glazing.

Mostly, the lower insulation around the resonance frequency is roughly compensated by the gains obtained in the mid/high frequency range. The value of this compensation is, however, dependent of the importance of the various frequency ranges.

Sound insulation is mostly viewed in terms of a reference spectrum for the noise source involved (see section 3.2). The shape of the sound insulation curve can have different effects on different sources of noise. Railway traffic noise has a lower sound level at low frequencies than road traffic noise. Since the use of heavy gases improves sound insulation in the mid frequency range, such usage will have more effect on rail traffic noise than road traffic noise. Such is the case because the noise level produced by road traffic is characterised to a greater extent by low frequencies, at which level insulation is not improved by using heavy gas in the cavity. For this reason, the improvement of single value sound insulation attained by using SF_6 in a specific glass assembly will be greater in the rail traffic spectrum than in the one for road traffic. The noise spectrum therefore also determines if SF_6 should be used.

The goal of this theoretical discussion is to relate the effects visible in the sound insulation curve to causes that can be explained in terms of the interaction between sound waves and the insulating medium. In practice, insulation curves cannot be solely calculated on a theoretical basis. The influence of edges and the like are not reproduced in the theory. This makes it difficult to derive the precise values in an exclusively theoretical exercise. To determine the sound insulation characteristics of structures in advance, it is preferable to employ empirical models based on earlier measurements.

3. SOUND INSULATION ON THE BASIS OF EMPIRICAL/CALCULATED DATA

3.1. Introduction

In chapter 2, the theory of the sound insulation performance of double-glazing was discussed. Determining the sound insulation of glazing is, in practice, based on empirical data and on an empirical-based calculation model. The composition of a given type of glass serves as input and, based on empirical correlation, can be used to calculate the sound insulation spectrum for that specific glass. A frequently used method is the calculation method presented in *Geluidwering Gevels (Sound Reduction by Facades)*, publication WG-HR-05-02 [4]. Possible kinds of glazing to be calculated in this method are single and double glass. In the calculation method presented in this publication, it is possible to use not only standard double-glazing, but also laminated glass with a 1 mm PVB film or a 2 mm resin layer. Furthermore, the cavity can be gas-filled.

The calculation is made using algorithms based on empirical data. This method is also grounded on the values for sound insulation provided in the *Herziening Rekenmethode Geluidwering Gevels (Revision Calculation method for Sound Reduction by Facades)*. This publication from 1989 will now be replaced by the *Nederlandse Praktijk Richtlijn (Dutch Application Guideline)*: Geluidwering in gebouwen - Aanwijzingen voor de toepassing van het rekenvoorschrift voor de geluidwering van gevels op basis van NEN-EN 12354-3, (2001) (Noise control in Buildings - Application guideline for the calculation of the sound reduction according to EN 12354-3(2001).) [7]. This paper is, at this time (March 2002), available in draft form. According to the *"Revision calculation method"*, the laboratory values employed in determining these sound insulation values have a 1.0 dB margin of error. With this margin, the effects of product differences, laboratory discrepancies and dimensions of the glass can be discounted.

NEN and ISO standards

To provide a simple way of comparing the sound insulation provided by various types of glazing, a number of single-number quantities for sound insulation have been defined. These values have been determined from a sound insulation curve such as the one shown in figure 2.1. In practice, a number of different single-number quantities are used. Which quantity is used depends on the situation. In The Netherlands, the A-weighted sound insulation as defined in the Dutch Standard: NEN 5079:1990 is often used for standard outside noise, because this spectrum for standard outside noise corresponds to the one for road traffic. Additionally, the sound spectra for rail and air traffic have also been established. These are also recorded in NEN 5079:1990. Moreover, the R_w value and R_{Atr} values defined in ISO 717-1:1996 are also used.

Dutch standard: NEN 5079:1990

This NEN standard establishes the criteria for determining the A-weighted sound insulation ($R_{A,V}$) for outside (road traffic) noise. The sound insulation curve for a type of glass is used in the following way to determine the $R_{A,V}$ value.

The starting point is the road traffic spectrum on the source side. Applied to this noise spectrum for road traffic is a standard correction (A-weighting) in order to factor in the frequency-dependent sensitivity of the human ear. This A-weighted spectrum for road traffic is recorded in the NEN standard. Based on this weighted noise spectrum and the sound insulation curve, the A-weighted noise-spectrum on the receiving side is determined. This is done by subtracting the sound insulation (figure 2.1) per frequency band from the A-weighted reference spectrum. The result is the A-weighted inside spectrum. The difference in the sound pressure level between the A-weighted road traffic noise and the A-weighted inside noise is then the "A-weighted" sound insulation of road traffic $R_{A,V}$. In the same manner, the $R_{A,r}$ and the $R_{A,l}$ for respectively rail traffic and air traffic can be determined.

International standard: ISO 717-1:1996

This ISO (International Organisation for Standardization) standard establishes the criteria for the Weighted Sound Reduction Index (R_W). For this purpose, the sound insulation spectrum (figure 2.1) is compared to the reference curve as recorded in the ISO, presented as dotted line in figure 2.1. This reference curve is shifted by 1 dB to the measured curve until the sum of unfavourable deviations is as large as possible but no more than a predetermined value. After this displacement of the reference curve, the value in decibels of the reference curve at the 500 Hz frequency provides the R_w value.

This same ISO 717-1 also establishes the R_{Atr}. It is a value that, just like the $R_{A,V}$ value, is determined by means of a reference spectrum. This reference spectrum greatly resembles the spectrum for traffic noise presented in NEN 5079. The R_{Atr} value is often not directly indicated, but provided by R_w and the "spectrum adaptation term" (C_{tr}); in such cases, it holds that $R_{Atr} = R_w + C_{tr}$.

The shape of the sound insulation curve can have a large influence on the single-number quantity for the sound insulation. To be more specific, a high sound insulation in the lower frequency range has more influence on a noise spectrum with a high sound level in this lower frequency range. It is therefore important to know which spectrum and, consequently, which single-number quantity is applicable to the situation involved.

3.2. Using the model to determine the effect of gas filling

In the *Revision Calculation method for Sound Reduction by Facades*, sound insulation is indicated by the A-weighted sound insulation for outside noise ($R_{A,V}$). In the draft Dutch Application Guideline, NPR 5272, R_{Atr} is used to indicate the sound insulation. Because, on the one hand, the NPR is still in the developmental phase and, on the other, the present data have particular relevance to the $R_{A,V}$, these $R_{A,V}$ values in the *Revision*

Calculation method will be used in the following analysis. The reference spectrum for determining the R_{Atr} value does not deviate significantly from the reference spectrum for determining the $R_{A,V}$ value, and the following analysis will therefore not deviate significantly for both characteristic values. For rail and air traffic noise, differences can indeed occur.

Based on the data in the *Revision Calculation method for Sound Reduction by Facades*, a comparison can be made between the sound insulation of gas-filled and air-filled glazing. For a number of $R_{A,V}$ values a glazing with and without SF_6 is selected which have that particular sound insulation $R_{A,V}$ value. The starting point for this selection is the requirement that the remaining properties (such as thermal insulation) are, as far as possible, kept constant.
No consideration is given to the effects of wind pressure in combination with glass dimensions on the minimal thickness of the glass.
If, in selecting the glass from the list, there are several possibilities, then the least expensive composition of cavity and glass is chosen.
The least expensive manner of improving the insulation of double-glazing is in the first place, the enlarging of the (air) cavity. This is also reflected in the data by the fact that the cavity is made as large as possible in a great many types of glazing. The maximum width of the cavity used in glazing is 24-mm. Using secondary glazing can attain a wider cavity, but this technique falls outside the scope of this text. A second (more expensive) step toward better sound insulation involves the use of thicker glass. The thickness of the various glass plates are combined in various manners in order to avoid such undesired effects as coincidence and the like, and consequently to achieve an optimal sound insulation. Additionally, an effort is made to make the total glass thickness remain as thin as possible in order to limit, in this way, the amounts of material used and costs incurred. A third step, and third in terms of its cost level, is the use of laminated glass (resin or film) for one of the glass plates. A last step involves using laminated glass for both panels.
The results attained in this manner are displayed in table 1. The composition of the glass is indicated as: glass thickness1/ cavity width/ glass thickness2. Laminated glass with 1 layer of PVB is indicated by a 1 after the glass thickness, laminated glass with cavity 2 mm acrylic resin is designated by the 2 after the glass thickness. For example: a glass panel of 6 mm glass, 2 mm resin and 4 mm glass is entered as 10.2. A panel with 6-mm glass, 1 layer PVB and 4 mm glass is recorded as 10.1.

Table 1 Possible glazing for the corresponding sound insulation Ra,v based on the *Revision Calculation method for Sound Reduction by Facades*

$R_{A,V}$ dB(A)	SF_6 filled	Air filled	Difference in cavity width (air - SF_6)	Differences in material (air - SF_6)
28	4/12/8	4/12/4	0	- 4 mm glass
29	4/20/4	4/12/6	-8 mm	+ 2 mm glass
30	4/16/6	4/24/4	+8 mm	- 2 mm glass
31	4/24/4	6/20/6	-4 mm	+4 mm glass
32	4/20/6	4/24/6	+4 mm	
33	6/26/6	6/20/10	-6 mm	+4 mm glass
34	6/24/10	8/24/12	0	+4 mm glass
35	6/24/12.1 4/24/10.2	8/24/12.1 6/24/10.2	0 0	+ 2 mm glass + 2 mm glass
36	6/24/10.2	8/24/10.2	0	+ 2 mm glass
37	8/24/10.2	8/24/12.2	0	+ 2 mm glass
38	8.1/20/12.2	10.2/20/10.2	0	- PVB + resin
39	10.2/24/10.2	10.2/20/10.2	-4 mm	

To enable a good comparison of air-filled and gas-filled glazing, the two right columns display the differences in the air cavity and the material between the two. It seems that the use of SF_6 does not always entail a reduction in required material. In general, 2 to 4 mm more glass is required to achieve the same sound insulation with air filling as that provided by an assembly involving SF_6-filled cavities. This difference appears to remain relatively constant for sound insulation values above 30 dB(A). More expensive laminated glazing instead of non-laminated glass does not seem to be necessary in order to acquire the same sound insulation. Costs will be further discussed in chapter 5.

3.3. Calculation program limitations

In using the calculation method or the *Revision Calculation Method* , a few limitations are encountered.

- With these programs, it is only possible to choose either gas or air filling. In practice, glass manufacturers often use mixed gases. Often, a mixture of Ar and SF_6 is used and may be combined in any proportion. The gas mixtures used for the measurements in Peutz's Acoustics Laboratory included a range varying from 70% Ar mixed with 30% SF_6 to 30% Ar combined with 70% SF_6. These proportions cannot be entered in the calculation model.

- In the case of laminated glass, a choice can only be made between a 1-mm-thick PVB film and a 2-mm-thick resin layer. It is not possible to vary the thickness of the film or to indicate its position. Glass producers experiment with different techniques and glazing assemblies in order to achieve the best possible sound insulation. Frequently, several film layers are used or the thickness of the resin layer altered, while the calculation model only allows 1 mm of PVB or 2 mm of resin. In addition, there are improved laminates on the market that, by means of a higher internal damping quality, have a greater effect on sound insulation than the films on which the model is currently based. These possibilities are taken into account neither in the calculation methods nor, at this time, in the tables included in the draft NPR 5272.
- A few doubts about the reliability of the results of the model exist. The following section will return to this subject.

4. SOUND INSULATION MEASUREMENTS

4.1. Introduction

Besides the data from the calculation model and the *Revision Calculation method*, the industry has over the year's commissioned a great number of measurements of the sound insulation of various types of glazing. These measurements have taken place at several laboratories. However since the first measurements were made, the standards (especially ISO 140-3) have been altered in ways that influence the accuracy of the measurements being made. Comparing the measurements of comparable types of glazing made in different laboratories and at different times (before and after the modification of ISO 140-3) shows a relatively wide variation.

In the context of the Amsterdam Airport Schiphol Sound Insulation Project, Peutz Consulting Engineers measured the sound insulation of an extended variety of glazing products. The measurements were made in the Peutz's Acoustics Laboratory during the period of January 2000 to February 2002. The measuring process involved the measurement of various double glass assemblies produced by different manufacturers under the same conditions in the same laboratory. This laboratory satisfies the requirements indicated by ISO 140-3 and is, among other things, accredited for measuring sound insulation by the Dutch Accreditation Commission (and is entered in the STERLAB registry under nº L334).

Analysis based on this data set benefited from the fact that the results attained were highly replicable. Measured differences were, therefore, attributable to differences in construction and not to laboratory discrepancies. The types of glazing measured were of various sorts. In addition to variations in glass thickness and cavity width, glazing with and without laminated glass was measured. Measurements were made of both acoustic insulation glass (hence with SF_6) and thermal insulating glass (hence without SF_6). The latter is especially very important for any attempt to provide alternatives to the use of acoustic insulating glass.

4.2. Determining the sound insulation

Sound insulation is measured according to ISO 140-3. The sound insulating construction is placed in an opening between two chambers. In one chamber, a diffuse but homogeneous sound field is generated by means of loudspeakers after which the sound pressure levels in both chambers are measured according to frequency. The sound insulation is calculated as:

$$R = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \qquad (4.1)$$

Where:

L_1 = sound pressure level in the transmitting chamber
L_2 = sound pressure level in the receiving chamber
S = surface of the object being tested
A = equivalent sound absorption [m^2] in the receiving chamber calculated according to the Sabine formula:

$$A = \frac{0.161V}{T} \qquad (4.2)$$

Where:

V = volume of receiving chamber
T = reverberation time in the receiving chamber

In this standard, the reverberation time and volume of the receiving chamber are both taken into account. The sound insulation determined in formula 4.1. is calculated for all frequency bands, on the basis of which a sound insulation curve is produced.

The measurements were made on glazing having the dimensions of 1,25 x 1,5 m (in accordance with ISO 140-3). After delivery, the glass panels stood at least 5 days in the laboratory in order to let the settings for the edges harden.
Sound Measurements were undertaken in measurement chambers 1 and 2 (see diagram in appendix 1) to determine the sound insulation by equation 4.1. They were made in both directions and subsequently averaged. In this manner, an improvement in the repeatability of the results was achieved.

The accuracy of the calculated sound insulation performances can be numerically expressed in terms of the repeatability r (within one laboratory) and the reproducibility R (between different laboratories). When sound insulation is measured twice in short succession using the same method on an identical object of measurement under similar conditions in the same laboratory, the probability is 95% that the difference between the two measurements will amount to a maximum of r.

When sound insulation is measured twice in short succession using the same method on an identical object in different laboratories, the probability is 95% that the difference between the two measurements will amount to a maximum of R.
The values with which the repeatability and reproducibility of measurements must comply are described in ISO 140-2. These values are indicated in figure 4.1. In addition, the standard of repeatability as determined in ISO 140-2 was attained at Peutz's Acoustics Laboratory in Mook, The Netherlands. In the presented measurements, it appears that

the repeatability r lies considerably below the repeatability requirements. Compliance with the repeatability standard set in ISO 140-2 is, therefore, more than adequate. Above the 200 Hz level, the repeatable measurement procedure resulted in a deviation of less than 1.0 dB. Consequently, good repeatability within the laboratory is demonstrated, a factor that also ensures a high reliability of the measurements discussed in this section.

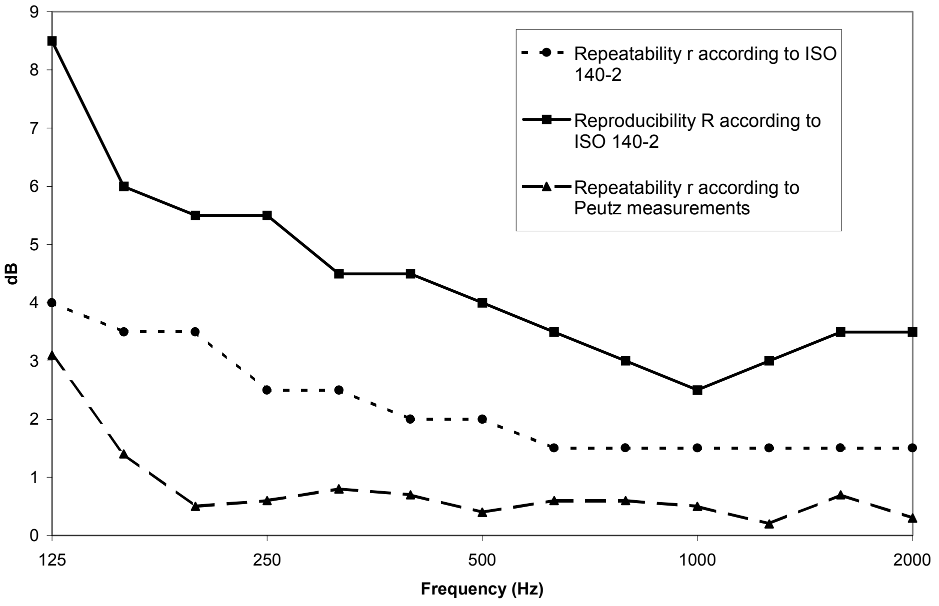

Figure 4.1 Repeatability and reproducibility requirements according to ISO 140-2 and the repeatability attained by Peutz's Acoustics Laboratory.

As indicated earlier, the sound insulation analysis provided in the context of this report is based on the road traffic spectrum $R_{A,V}$. This spectrum is, in practice, the one most frequently used. Values in this spectrum were determined in Peutz's Acoustics Laboratory for various types of glazing and involving glazing products from various manufacturers.

First, a comparison was made between the measured sound insulation performances and those expected by the results of the empirical calculation model discussed in chapter 3. In converting the material composition of the glass assembly, as reported by the manufacturer, into data employable in the calculation model, the following assumptions were made:

- If the manufacturer indicated that SF_6 or "an acoustic gas" was used as cavity filling, then this was taken into account in the calculation model.
- If the manufacturer indicated that a gas mixture of SF_6 and argon was used, then this was recorded as acoustic gas if the SF_6 amounted to at least 70 % of the total gas (also see draft NPR 5272); if a lesser amount of SF_6 was indicated, then the gas-filling was measured as if it were reported as being "mixed filled."

- One or more films in laminated glass were recorded as 1 layer of PVB film.
- Resin layers were, independent of their thickness, entered as laminated glass with resin as elastic layer.

To enable distinctions to be made in the analysis, the glass types were subdivided into six categories:

Category
1: air-filled, non-laminated
2: air-filled, laminated
3: gas-filled, non-laminated
4. gas-filled, laminated
5. mixed filled, non-laminated
6. mixed filled, laminated

In the NPR 5272 the cavity is considered to be gas filled when the cavity gas consist of at least 70% SF_6. The measurements discussed in this chapter involve many different gas compositions. In this text a gas filling composed of 70% or more SF_6 is assigned to category 3 or 4, and 100% air filling to 1 or 2. The intermediary cases do not belong to any of the categories 1–4. The categories 5 and 6 consist of glass types that contain some $SF_{6,}$ but at concentrations lower than 70%. The sound insulation of these categories is calculated on the basis of air-filled glazing.

In figure 4.2, the measured sound insulation of the various types of glazing is plotted against the calculated sound insulation derived from the calculation method [4]. Figure 4.2 also displays the extrapolated line $R_{A,V}$(laboratory) = $R_{A,V}$(calculation). If the calculated values are equal to the measured values, the points must all be located on this line. As mentioned above, the *Revision Calculation method* employs a margin in which the sound insulation measured in the laboratory must, on average turn out to be 1.0 dB(A) higher than the values generated by the calculation model. When the measured sound insulation is plotted against the calculated sound insulation, the points must lie in a straight line conforming to $R_{A,V}$(laboratory) = $R_{A,V}$(calculation) + 1dB(A). This is indicated on the graph as a dotted line. It shows the assumption that the laboratory values are 1 dB(A) higher does not agree with the results. Instead, this series of measurements indicates that the distribution of the measured values around the calculated values is markedly greater than what is described in the *Revision Calculation method*.

On the basis of this comparison, the following observations can be made:

- The largest underestimates (of not less than 3 to 5 dB(A)) occur for non-laminated glass, both for air- or gas-filled. It should be noted that this glass type is, in practice, also the most frequently used one in residential insulation.
- It could be the case that gas-filled glazing is recommended despite the fact that its use will not provide the required values.

- Air-filled laminated glass does not display any underestimates. In a few cases, the measure air sound insulation is clearly higher than that which is calculated (as much as ca. 8 dB(A)). The latter is probably caused by innovations in laminated glass (the sound-damping films). These films could therefore be more frequently used as an alternative than is predicted by the current calculation model.
- In the case of gas-filled laminated glass, both over- and underestimates by the calculation model can be observed.

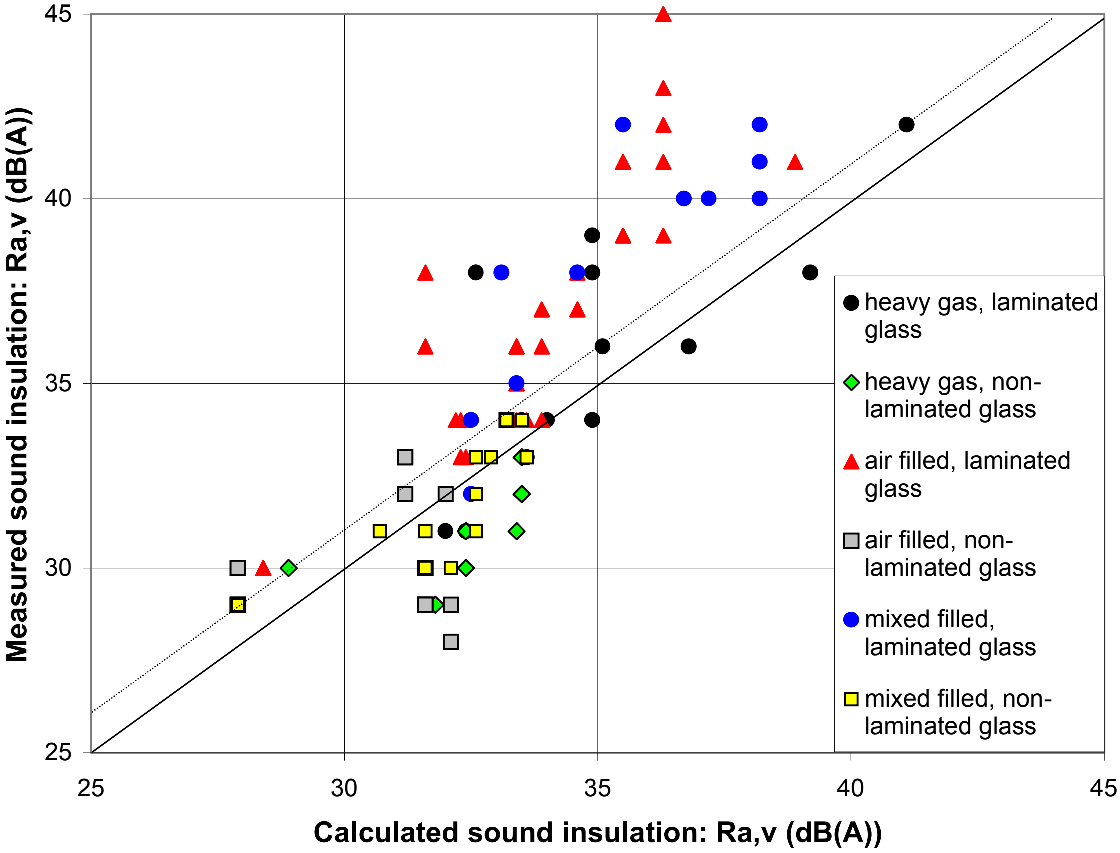

Figure 4.2 Measured sound insulation plotted against calculated sound insulation

Figure 4.2 clearly indicates that the sound insulation of double-glazing cannot accurately be predicted by the calculation method. Such is the case for both non-laminated and laminated glazing, the latter has been subject to many product innovations in recent years.

Consequently, the sound insulation values recorded in the draft NPR 5272 also fail to offer sufficient assurance that they can be realised in practice. It would be better to refer to the measurement results provided by manufacturers than to record adjusted figures based on these measurements.

Furthermore, the margin between laboratory measurements and the expected practical values also needs to be reconsidered. On account of the anticipated discrepancies between laboratories and the effects of such other factor as the dimensions of the glass, hardness of the settings for the edges, etc., the 1.5 dB total is insufficient. Depending on the required degree of assurance, margins of 3 to 5 dB(A) are necessary.

4.3. Glass selection on the basis of measured results

In table 1 of chapter 3, a prediction is made about the type of glazing needed to attain a given level of sound insulation. This is done on the basis of the data from the *Revision Calculation method* and the NPR, which in turn are based on the calculation method. In this section, a similar table will be set up, but one based on the single-number quantity for the sound insulation measured in the laboratory. Again in this case, the purpose is to investigate the possibilities of attaining a given sound insulation using gas-filled and air-filled constructions. To this end, a list is compiled of the sound insulation (for which the $R_{A,V}$ value is used) of gas-filled assemblies next to an alternative list of construction without gas filling.

It does not appear to be possible to provide a gas-filled and air-filled alternative for each insulation value on the basis of the measurement data set. The empty positions are indicated in table 2 by an asterisk. The results appear to be rather more arbitrary than the values presented in table 1 on the basis of the calculated data. For certain sound insulation levels, the quantity of material is the same; in no case is more than 4 mm of extra glass needed in order to attain the same sound insulation values without using SF_6 as an assembly with SF_6. This agrees with the results obtained in section 3.4. Neither table 1 nor table 2 indicate any need to use the more expensive laminated glass in the case of air filling to attain the same sound insulation as an SF6-filled construction.

It should be noted that, in a few cases, gas-filled glass with only 60% SF_6 is indicated. According to the draft NPR, this is less than the minimum level required for acoustic glass (>70%).

Table 2 Possible types of glazing for corresponding sound insulation levels as determined by measurements at Peutz's Acoustics Laboratory

$R_{A,V}$	SF$_6$ filled	Air/Argon filled	Difference in cavity width (air - SF$_6$)	Material differences (air - SF$_6$)
28	*	8/24/4	*	*
29	5/15/8	6/15/4	0 mm	-3 mm glass
30	4/24/6	4/15/6	-9 mm	0
31	4/24/6	*	*	*
32	8/24/5	5/20/8	-4 mm	0
33	8/24/5	10/15/6	-9 mm	+3 mm glass
34	*(60% SF$_6$ 40% Ar)* 10/24/6	10/24/6	0 mm	0
35	6/20/6-1-6PVB	6/20/6-1-6PVB	0 mm	0
36	5-1-5Resin/20/6	5-1.5-5Resin/12/10	-8 mm	+ 0.5 mm resin +4 mm glass
37	*	44.2EP/24/12	*	*
38	*(60% SF6 40% Ar)* 12/24/4-2-4PVB	4-2-4film/24/12	0 mm	0
39	4-2-4PVB/20/6-2-4PVB	8-2-6Film/24/4-2-4Film	+4 mm	+4 mm glass
40	10/24/5-1-5Resin	*	*	*
41	5-2-5Resin/20/5-2-5Resin	5-1.5-5/24/5-1.5-5	+4 mm	-1mm resin
42	8-2-6Film/24/4-2-4Film	8-2-6Film/24/6-2-6Film	0 mm	+4 mm glass

5. COST ANALYSIS

5.1. Introduction

Chapters 3 and 4 contain a discussion about which types of glazing should be considered in order to meet a given sound insulation requirement. In this regard, the differences between SF_6-filled and air/argon-filled double glass were analysed. Based on the data, it appears that the differences can be reduced to a few millimetres of extra glass thickness in the SF_6 free case. In chapter 4, it was also noted that, in the discussion of the measured types of glazing, no consideration was given to the kind of material from which the elastic intermediate layer in laminated glass plates was constructed. Manufacturers are attempting to improve the acoustic quality of glazing by using such an elastic layer. Special acoustic films are being developed and used to improve these sound insulating quality. Additionally, the costs of the different sorts of laminated glass using diverse films can vary.

In the comparison of costs, more factors are involved than just the direct acquisition costs of the glass. These include the following:
With argon/air filling, a higher thermal quality can be attained than with SF_6. This feature has a beneficial effect on energy use. More will be said about this in section 5.3. This benefit has not been previously considered in cost comparisons.
The total thickness of the glass assembly increases with the thickness of the glass and the width of the cavity. The consequence of this factor is that a heavier frame and/or frame wood must be chosen. More will be said about this in section 5.4, and this element is given consideration in the cost structure.

5.2. Cost price of glass

To make a reliable comparison of the costs of glazing with SF_6 or air/argon filling, this section provides a discussion of the cost price for diverse types of glazing. This is based on the recommended price per m^2 provided by glass suppliers. These averaged prices are listed in table 3.
It should be noted that the list contains averaged prices based on a survey of several suppliers, and that the prices among suppliers can vary greatly. The range of prices is also indicated in the table.
The results show that, for sound insulation up to 32 dB(A), gas-filled glass is, in general, more expensive than the air-filled equivalent with the same sound insulating quality. For higher levels of sound insulation, the gas-filled variant is, in general, less expensive. For two sound insulation values 34 and 38 dB(A)), this difference is 19%. This price difference lies in the same order of magnitude as the range of prices among suppliers of the same glass.

Table 3 Cost-of-glass analysis based on data from manufacturers

		SF_6 filled				**Air filled**					
Nº.	$R_{A,V}$ dB(A)	Composition	Total glass thickness (mm)	Glass price (€/m²)		Composition	Total glas thickness (mm)	Glass price (€/m^2)		Glass price difference (SF_6–air) (€/m^2)	Diff. as % of glass price for SF_6-glass
				avg	*range*			*avg*	*range*	*average*	*%*
1	28	4/12/8	24	35.72	32-40	4/12/4	20	23.27	21-25	12.45	35%
2	29	4/20/4	28	31.23	25-35	4/12/6	22	26.75	24-28	4.66	15%
3	30	4/16/6	26	30.98	28-34	4/24/4	32	27.71	25-31	3.27	11%
4	31	4/24/4	32	32.98	27-37	6/20/6	32	33.13	29-36	-0.16	0%
5	32	4/20/6	30	34.75	30-39	4/24/6	34	30.88	27-34	3.86	11%
6	33	6/24/6	38	40.12	35-47	6/20/10	36	43.00	38-47	-2.88	-7%
7	34	6/24/10	40	49.57	43-57	8/24/12	44	59.11	50-63	-9.54	-19%
8	35	6/24/12.1	43	70.77	54-81	8/24/12.1	45	71.97	59-78	-1.20	-2%
		4/24/10.2	40	94.11	74-103	6/24/10.2	42	90.51	77-100	3.60	4%
9	36	6/24/10.2	42	94.12	77-106	8/24/10.2	44	95.73	82-107	-1.61	-2%
10	37	8/24/10.2	44	99.70	83-113	8/24/12.2	46	100.95	88-118	-1.25	-1%
11	38	8.1/20/12.2	43	120.89	98-143	10.2/20/10.2	44	143.95	118-162	-23.06	-19%
12	39	10.2/24/10.2	48	148.84	121-168	10.2/20/10.2	44	143.95	118-162	4.88	3%

5.3. Thermal insulating glass

In the analysis of all the types of glass in this study, the glazing was selected on the basis of the acoustic quality of the glass. In practice, thermal insulation is, however, also a relevant fact when glazing is concerned.

The use of SF_6 in acoustic insulating glass has a negative effect on the thermal insulation of the glazing. Compared to air/argon, SF_6 is a better thermal conductor of heat. In contrast, double-glazing with a cavity filled with argon improves thermal insulation over an air-filled assembly. Argon has, however, no significant effect on the sound insulating quality. Given that argon is not a greenhouse gas, there is not any problem in referring to it as a non-heavy gas, just as air is.

The better thermal insulation is transferable into energy savings. By converting this saving into costs, it is possible, in principle to determine the extent to which the saving compensates for the initial level of investment. This return has not previously been given consideration.

When choosing a type of glazing, it is important to take into account the thermal insulating requirements that the relevant building must meet. In this regard, it should be noted that the HR++ quality (U≤1.2 W/m2K) couldn't be achieved with SF_6-filled glass. In situations requiring this level of thermal insulation (because of energy regulations within the Building Code or other environmental measures), SF_6 is not a possibility at all. The trend is that more and more HR++ glazing is being used. In any event, general practice is that compliance with such contradictory requirements is not or hardly verified. The glass actually installed fails to meet either acoustic or thermal requirements.

5.4. Elaboration

In discussing costs, it is certainly important to consider all additional costs of materials. In addition to the costs of the glass, the costs for the window frame and frame wood have to be considered. In choosing thicker glass, a thicker (more expensive) frame could also be required. This factor could, in some cases, mean that the use of air-filled glass having glass panels that are a few millimetres thicker transgresses the limit of a certain frame and a more expensive thicker frame is needed. A distinction should be made between glazing for the fixed frame and the movable window frame . It appears that, in general, thicker fixed frames are not required for the installation of thicker glazing. The specifications are indeed altered, but this change does not have any significant consequences in terms of costs. The influence of the thickness of the glazing on the dimensions of a frame for the movable part of a window are indeed relevant and will be further elaborated in this section.

For an open-swinging window, a thicker window frame is required once glass thickness reaches 31 mm. For glazing up to 31 mm thick, 67 x 102 mm frame wood can be used. For glass thicker than 31 mm, the smallest wood that can be used is 80 x 114 mm. Prices of frame wood are listed in terms of linear meters; the extra cost of the heavier frame wood is on the order of €1/m’. A subsequent changeover point is situated at 45 mm thick glass. At this point, another set of specifications is needed, and the costs amount to an additional €1/m’.

The costs of frames are calculated per linear meter, while the costs of glazing are indicated per m² glass The publication "*Novem-referentiewoningen*" *(NOVEM Reference Dwellings)* [8] establishes the amount of m’ frame wood needed per m² glazing. In this regard, the sunroom residence (town house residence) is used as a reference. It indicates that 5 m’ of window frame wood is needed per m² glass.

For the opening portion of a window, a conversion to glass thicker than 31 mm would entail a price increase of €5 per m^2 glass. For glass thicker than 45 mm, another set of specifications must be used; the extra costs also amount in this case again to an additional €5/m^2, and therefore €10/m^2 in comparison with glass thinner than 31 mm. For glazing installations that, because of the use of air-filled instead of gas-filled glass, transgress the above-mentioned boundaries, the extra costs of the required frames are listed in table 4. Following ultimately from this list, the last two columns provide the price difference between gas-filled and air-filled glazing, the second from last column lists this difference in €/m^2 and the last column as a percentage of the glass price for SF_6-filled glazing. Additionally, the price difference is listed so that a positive difference indicates an increased price for SF_6-filled glazing.

Table 4 Costs including frame

	SF_6 filled			**Air filled**				
N°.	Total glas thickness	Extra costs of glass thicker than 31 mm	Extra costs of glass thicker than 45mm	Total glass thickness	Extra costs of glass thicker than 31 mm	Extra costs of glass thicker than 45mm	Differences in the extra costs of frame wood (SF_6–air)	Total price difference of glazing and frame (€/m^2) (SF_6–air)
1	24	-	-	20	-	-	0	13
2	28	-	-	22	-	-	0	5
3	26	-	-	32	5	-	-5	-2
4	32	5	-	32	5	-	0	0
5	30	-	-	34	5	-	-5	-1
6	38	5	-	36	5	-	0	-3
7	40	5	-	44	5	-	0	-10
8	43 40	5 5	-	45 42	5 5	- -	0 0	-1 4
9	42	5	-	44	5	-	0	-2
10	44	5	-	46	-	10	-5	-6
11	43	5	-	44	5	-	0	-23
12	48	-	10	44	5	-	5	10

Of note is the fact that this approach is only applicable to the construction of new residences having wooden window frames. When synthetic or aluminium frames are used (residential or public utility buildings) other considerations are applicable. Often, there is then a question of a maximum glass size. Exceeding this glass size can have such great consequences that another system must be chosen. Since the maximum sizes may vary from system to system and since the consequences in terms of costs cannot be indicated in advance, this issue will not be discussed further.

6. CONCLUSION

This study has principally investigated the economic consequences of not using SF_6 in the cavity of double-glazing. SF_6 is a heavy gas and has, when used as a cavity filling, a generally positive effect on sound insulation.

Based on empirical data and measurement data obtained in Peutz's Acoustics Laboratory, this report identifies alternatives for gas-filled glazing.

A comparison of measured and calculated data reveals that the usual empirically based calculation models are not sufficiently accurate in their calculations of the sound insulation of double-glazing. Given that the actual choice of glazing types available are mostly based on the empirical calculation models, it is quite possible that the types of glass chosen in practice provide an inadequately low level of sound insulation.

Before a choice of glass is made, its sound insulation performance should be verified on the basis of measurement data collected in a certified laboratory in order to ascertain if the glazing actually provides the required sound insulation. In doing this, a margin of 1.5 to 2 dB is to be used in order to compensate for the influence of dimensions, frames, etc.

The average costs of gas-filled and air-filled glazing have been determined and compared. The glass price differences shown in table 3 indicate that the differences in costs between SF_6-filled and air-filled glazing are not very constant. For lower A-weighted sound insulation quantities $R_{A,V}$ (28 dB(A) to 32 dB(A)), table 3 indicates that the prices of using SF_6-filled glass are higher. The use of SF_6 does not have, in this case, any benefit for the sound insulation of the glazing. Types of glazing with sound insulation values in this range are, in practice, the most frequently used formats.

This finding indicates that, for standard uses of glazing in residential construction, the installation of SF_6-filled glass is not an alternative for air-filled glazing. For the frequently used sound insulation values up to 32 dB(A), the use of SF_6-filled glass is even more expensive than air-filled glazing.

For sound insulation values above this 32 dB(A), prices are generally higher for air-filled than for SF_6-filled glass, although it is to a limited degree. The highest extra costs occur for glazing with sound insulation levels of 34 and 38 dB(A). At these levels, additional costs amount to ca. € 10 and € 23 (=19%) respectively. These differences lie in the same order of magnitude as the differences in prices for the same products charged by various manufacturers. Therefore, the additional costs are, even for these two sound insulation levels, hardly significant.

The additional costs resulting from the use of heavier frames and frame wood appear only to have a limited influence on the total costs.

In sum, we can conclude that there is not any decisive acoustic or financial consideration justifying the use of SF_6 as a cavity filling.
The use of air- or argon-filled cavities is to be preferred, insofar as the desire to limit greenhouse gas emissions and to increase thermal insulation to an HR++ quality is concerned.

This report contains 39 pages. Mook,
1 Appendix

7. LITERATURE

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[3] H. Ertel, M.Finkenberger, F.P.Mechel, Zum einfluß von Gasfüllungen auf die Schalldämmung von Isolierglasscheiben im Resonanzbereich, IBP Mitteilung, 10 (1982) Neue Forschungsergebnisse

[4] Rglas-Rglas92, sound insulation program by TNO-TPD

[5] BASlab, computer program, Stichting Bouwresearch, (1997)

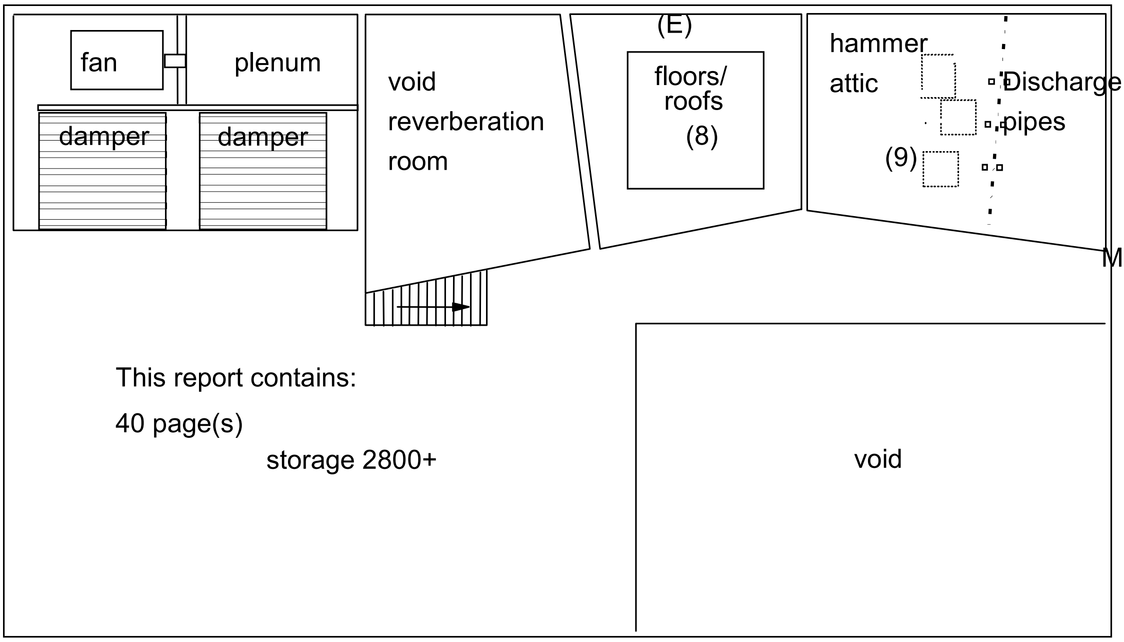
[6] Herziening Rekenmethode Geluidwering Gevels, VROM publication 112 (1989), *Revision Calculation method for Sound Reduction by Facades*

[7] Draft NPR 5272, Geluidwering in gebouwen - Aanwijzingen voor de toepassing van het rekenvoorschrift voor de geluidwering van gevels op basis van NEN-EN 12354-3, (2001), *Noise control in Buildings - Application guideline for the calculation of the sound reduction according to EN 12354-3(2001).*

[8] Novem, Referentiewoningen 98, *NOVEM Reference Dwellings*

Appendix 1

Upper floor

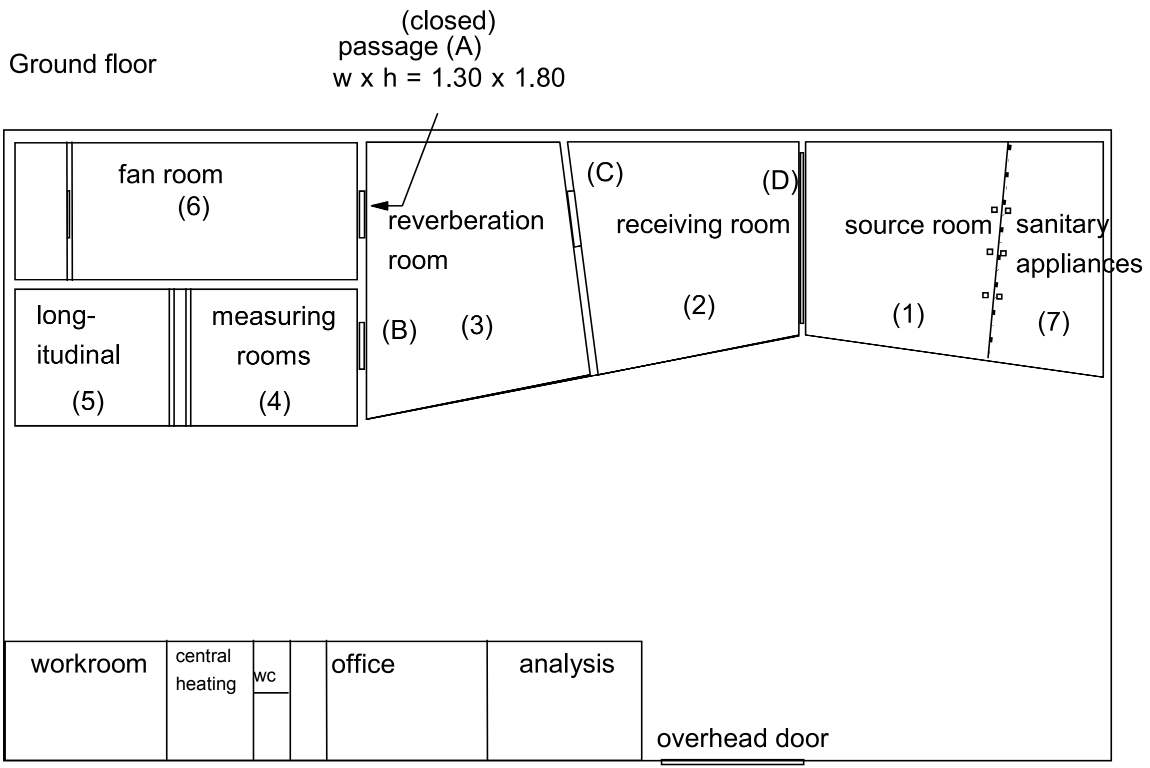


Mook,

This report contains:

40 page(s)

Ground floor



MEASURING GAPS (w x h in mm):

(B) 1000 x 2200
(C) 1500 x 1250
(D) 4300 x 2800
(E) 4000 x 4000