Field study on gas ducted heating systems in Victoria

Graham Palmer

B.Eng (Hons)

A minor thesis submitted to RMIT University in partial fulfilment of the requirements for the degree of Master of Engineering (Sustainable Energy) and to Sustainability Victoria

School of Aerospace, Mechanical and Manufacturing Engineering

RMIT University

September 2008

Declaration

This is to certify that:

1. except where due acknowledgement has been made, the work is that of the candidate alone;
2. the work has not been submitted previously, in whole or in part, to qualify for any other academic award;
3. the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program;
4. any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Signed: ....

Contact details:

Graham Palmer

Paltech Corporation

8 Kingston Park Court Knoxfield, Vic. 3180

(03) 9212 7777

graham@paltech.com.au

Contents

List of figures

List of tables

Abstract

Gas ducted (central) heating is widely used in Melbourne, and other regions within Victoria having access to mains gas, and provides affordable, comfortable and effective heating. However the use of ducting contributes to energy losses, leading to an increase in householders' energy costs, and an increase in greenhouse emissions. Many studies have been conducted in North America on similar systems, and have shown that losses typically range from 25 to 40 percent, however there have been no published studies up to date in Australia that have quantified the losses in Australian systems. Energy losses due to ductwork are composed of thermal losses, which are caused by the unwanted propagation of heat through the duct walls and fittings, and leakage losses, which are due to unwanted air leaks in duct, fittings and equipment.

With the support of Sustainability Victoria, a field study was conducted on ten homes in Melbourne to quantify the energy losses due to ductwork. The field study involved testing the central heating systems of homes that were from nine to thirty years old, followed by replacement of the ductwork, followed by re-testing. Additionally, two test rigs were constructed to validate some of the factors influencing energy losses, and included the construction of a thermal test rig to dynamically measure the steady state thermal conductivity of flexible duct, and a rig to measure the air leakage from flexible duct joins using the PVC tape in common use in Victoria.

The pre-retrofit testing showed energy losses due to ductwork of between 26 and 58 percent, reducing to losses of between 10 and 18 percent after the replacement of the ductwork. Including the gas furnace (heater) efficiency, the pre-retrofit total system efficiency ranged from 30 percent, up to 69 percent. The post-retrofit system efficiency, including gas furnace, was between 50 and 76 percent. On average, the improvement of the system efficiency of the systems, in terms of energy delivered into the living space relative to the natural gas consumed, was 30 percent for the systems that were more than 15 years old, and 14 percent for the systems that were less than 15 years old.

Given the age of the systems, most of the systems used furnaces that would be graded from one star to four stars using the current star rating. One home had a replacement furnace, which had a 5 star rating. In theory, with the use of a five and a half star furnace, with R1.5 m^2.K/W duct, a system efficiency of 85 percent should be achievable in Melbourne.

Expressed in terms of emission abatement cost (assuming an amortisation period of 15 years, discount rate of 7 percent, and a gas cost of 1 cent/MJ), the greenhouse abatement cost averaged $33 per tonne CO2-e avoided for the homes that were greater than 15 years old. Under the same scenario, with an increase in gas price to 1.5 cents/MJ, the abatement cost averaged to a negative cost of $45 per tonne CO2-e avoided. For the homes that were less than 15 years old, the payback periods were longer and the abatement costs higher.

There would be a benefit for all, except one household, in upgrading their furnaces. However the replacement of the ductwork was a more cost effective option for the older systems. For systems that are less than ten years old, the choice of replacing the ductwork only, rather than the furnace only, is less clear, and it may be more cost effective to replace the furnace with a high efficiency unit. The estimated thermal resistance of the duct in the pre-retrofit systems was R0.6 m^2.K/W. For the homes in the field study, the replacement of the ductwork was a more cost effective option than installing additional wall or ceiling insulation.

The use of semi-rigid aluminium duct from the early 1970's up to the mid 1980's is prone to substantial leakage through the breakdown of the polyethylene sleeve, and at the duct-to-fitting connections. The problem with this type of duct is that it has perforations along its length to reduce the audible noise through the duct (duct can still be produced with perforations and is referred to as acoustic duct). This has the side affect of leading to substantial leakage once the outer sleeve has broken down, through damage or degradation, or the duct-to-fitting join has deteriorated. The systems that were less than 15 years old performed significantly better in the leakage test.

The duct-to-fitting connections showed deterioration in some cases, and were one of the contributors to leakage. The duct tape in the systems that were around thirty years old had lost their tack completely, although the duct-to-fitting joins remained intact if sufficient tape had been used, the tape was wound sufficiently around the individual components, and the join was left untouched. The tape in the systems between nine and fifteen years old was in good condition, and retained most of the original tack. The longevity of the join was dependant on using sufficient tape, taping both the inner core and outer sleeve, and maintaining sufficient tape on the collar of the fitting. If any of the conditions were not met, the join was more likely to have deteriorated.

Beginning the mid 1980's, there was a shift in the type of flexible duct used in residential systems. Rather than using aluminium strip, the duct was manufactured with a core composed of a lighter grade plastic film or fabric, which gave the duct compressibility. The duct did not use the perforations that were in common use in the semi-rigid duct used earlier. One of the benefits of the non-perforated duct is that it retains most of its air sealing capabilities if the outer sleeve is damaged or broken down. There were a number of cases where there seemed to be damage to compressible duct, but the systems retained good air tightness.

In some cases, the ductwork showed damage due to the original installation, or from some other causes, such as animals under the house. In many cases, the householder is unaware of the damage or deterioration to ductwork, although some householders commented that they felt the heating wasn't as effective as it should be.

The shift to plastic fittings, which occurred from the late 1980's, has had the unforseen benefit of providing excellent protection against leakage that has been present in North American systems, provided that the system is correctly installed, with good quality components. It is noteworthy that the quality of installation of central heating systems in Victoria is largely left to the market with virtually no regulatory checking taking place.

The thermal performance of the ductwork was improved with the use of R1.0 m^2.K/W or better duct, with insulated fittings. In some of the homes, R1.5 m^2.K/W duct was used, which provided excellent thermal performance. There would be little additional benefit in using a duct thermal rating higher than R1.5 m^2.K/W, and the additional cost may not be justified.

1. Introduction

1.1 Aims

The aim of the field study is to determine the energy efficiency of the ductwork of the gas ducted heating systems examined in the field study, both before and after changing the ductwork. The relationship between the level of insulation of ductwork and the energy efficiency of the ductwork will be determined. The causes of reduced energy efficiency of ductwork, and possible solutions will be assessed.

1.2 Research questions

How much energy is lost through ductwork?
How is the energy lost?
What contribution does this loss make to Victoria's greenhouse emissions?
What is the contribution of thermal losses and leakage losses respectively?
Are there other factors that contribute to the energy loss?
Can the energy loss be reduced?
How much does it cost to reduce the losses, and what is the cost/benefit of the reduction?
How does replacing ductwork compare with other energy efficiency options available to a householder?

1.3 Scope

The study is limited to residential gas ducted heating systems in Melbourne, and does not include non-ducted gas space heating. The study focused on systems that are 10 years or older. Although the gas furnace performance is examined, the operation and efficiency of the furnace is not the primary focus of the study. A range of other heating options are briefly assessed to allow comparison with gas ducted heating. A historical background of gas ducted heating and its relationship to the development of the mains gas network in Victoria is provided to provide a context to the research questions.

2. Background and context

The development of gas ducted central heating in Victoria from the early 1970's is closely related to the development of natural gas. It was the availability of an inexpensive, clean, piped energy source, together with development within the ducted heating industry of equipment and fittings at affordable prices, which spurred the development of central heating. Gas ducted heating has brought comfort to the masses through the availability of both affordable equipment and inexpensive energy. Gas ducted heating is the main form of heating in 40.1% of Victorian households (ABS 2005a).

2.1 Historical overview of gas supply and gas ducted heating in Victoria

Gas has been sold in Victoria since 1844, and Victoria relied on town gas, produced from coal, for the following 130 years. Victoria's first gas utility, the Melbourne Gas and Coke Company, first supplied Melbourne with town gas in 1856 (Proudley 1987). During the period 1856 to 1890, many private gas utilities were established, often with overlapping geographic boundaries, with as many as 50 gas works being developed by the end of the nineteenth century. The period up to the Second World War was very successful for the private gas utilities. However coal shortages, high coal prices, and increased labour and capital costs in the period during, and after, the war were challenging for the industry (Productivity Commission 1995).

The most common process to produce town gas was from black coal using the carbonization process. This involved heating crushed bituminous coal to high temperatures, releasing gas and coke. The gas required several stages of cleaning, scrubbing, cooling, treating and purifying to produce usable gas (New South Wales EPA 2007). Town gas is typically composed of mostly hydrogen and methane, with carbon monoxide and carbon dioxide (Plambeck 1996).

Victoria relied on black coal for the production of gas and electricity, imported from New South Wales, until the middle of the twentieth century. New South Wales possessed large deposits of high grade black coal, which had been used since the mid 1800's. This gave New South Wales a considerable economic advantage in manufacturing industries, as well as iron and steelworks. Victoria's brown coal was always considered a second rate resource, primarily because of its high moisture content. The state government established the State Electricity Commission of Victoria in 1921 primarily because of its desire to develop the low grade brown coal reserves of Latrobe Valley, and thus reduce the State's dependence on the strike prone black coal industry of New South Wales (Abbott 2006).

In 1950, the State Government announced that it would establish a Gas and Fuel Corporation, which would control fuel, allowing the State Electricity Commission to concentrate on electricity, which had been recognized as the main growth use of brown coal. Under this legislation, the Government took over two of the three main gas utilities in Melbourne - the Metropolitan Gas Company and the Brighton Gas Company (Edwards, 1969). Its objective was to replace reliance on New South Wales black coal with a new brown coal plant at Morwell, using the German developed Lurgi gasification process, which was achieved in 1956 (Edwards 1969).

Up to the Second World War, wood burnt in open fireplaces was the main method of heating houses, and slow combustion stoves using coke were used for a while in the post-war years (Morse 1988). At the start of the 1960's, briquettes and wood were the main sources of heating (ABARE 2007). Beginning around 1962, heating oil started being used for heating, largely displacing briquettes. It was during this time that Victoria saw the first oil central heaters.

As well as the Lurgi gasification process, gas was being produced with imported petroleum products through the 1960's. The raw materials for gas were in a state of flux during this time, and in 1966, thirty percent of gas was being produced from residual oil, thirty percent from refinery gas and LPG, thirty percent from Lurgi gas, and less than ten percent by carbonization of black coal (Proudley 1986).

During the 1950's, Australia had no significant indigenous oil or natural gas and it was considered unlikely that commercial quantities would be discovered (Morse 1988). However by 1960, the Gippsland Basin, off the Victorian east coast near Lakes Entrance, had been identified as having structures prospective for oil and gas. In 1964, the first gas flowed from a well in the Barracouta field. Two years later, another gas field was confirmed at the Marlin structure. With these discoveries, the Gas and Fuel Corporation of Victoria, together with three other smaller gas marketers – Colonial Gas, Geelong Gas and Gas Supply Co – began negotiations with Esso and BHP to purchase gas, leading to a twenty year contract beginning in 1967 (Productivity Commission 1995). Natural gas was introduced in Melbourne in 1969. Victorian natural gas typically consists of 90% methane, 6% ethane, and other elements and compounds. (Energy Networks Association 2007)

Following the introduction of natural gas, town gas appliances needed to be converted, and by the end of 1970, one million appliances had been converted (Proudley 1987). The conversion in Melbourne took place over a 20 month period, ending in December 1970, and was divided into three distinct stages: sectionalisation that required the installation of 1700 valves to isolate consumers into groups of 3000 households, pre-conversion which required a survey of all appliances to be converted, and the conversion itself, which required an intensive change-over to natural gas, burning off of town gas, and appliance conversion (Proudley 1987). At this time, town gas was primarily used for cooking, with heating using primarily oil, briquettes and timber. Following the introduction of natural gas, gas central heating started displacing oil central heating, beginning a period of rapid market penetration in Victoria. The popularity of natural gas heating accelerated from the late 1970's when the price of heating oil rose sharply. Firewood also gained in popularity for a number of years, peaking in 1992 (Todd 2003).

Central heating systems required three main sets of components, the furnace, fan, and ductwork. In the early stages of central heating in Victoria, the fittings were mostly manufactured locally by sheet metal fabricators, with some components being imported from North America - Canada and the United States already had established central heating markets, and research had already been conducted on the development of flexible duct in the 1960's (for example, Schroeder et al. 1965). The larger companies focused on the equipment, leaving the ductwork fabrication to mostly smaller companies. Vulcan was the exception to this model, producing both equipment, and ductwork components, which it continued to do until it left the ductwork market in the late 1980's. Vulcan promoted the advantages of purchasing "a complete system" citing energy efficiency advantages. Vulcan claimed to use more powerful fans, which allowed the use of small duct, with the accompanying cost benefits and thermal loss reductions. While much of the industry was using 6 and 8 inch duct at the supply end of the system, Vulcan promoted the advantages of 5 and 7 inch duct. The equipment manufacturer, Brivis, also briefly entered the ductwork market in the 1980's with its own range of fittings. Although there has been some market consolidation from time to time, the ductwork market is dominated by a large number of small to medium sized manufacturers and distributors, which operate distinctly from the equipment manufacturers. The lack of a clear demarcation, in terms of pricing and supply, between manufacturers, distributors, retailers, trade customers and retail customers, within the ductwork industry, has also discouraged the entry of large corporations into the market.

The duct and fittings were originally insulated with glass wool blanket, which was wrapped around the components. In the early 1970's, ductwork manufacturers began using sprayed polyurethane foam to insulate fittings, revolutionizing the fittings market.

It was during this period that Vulcan introduced its first generation "Sidewinder" flexible duct, which was semi-rigid, non-compressible and perforated with holes to reduce noise. Its main advantage was that it could be bent on site, making it far easier to install a system compared to solid sheet metal duct. It was constructed of corrugated aluminium and insulated with glass wool with a polyethylene sleeve. Although not obvious at the time, the use of perforations has significantly increased air leakage in systems. A number of manufacturers were producing a range of similar ducting products in the mid 1970's including, for example, Rayson, Romet Industries, Vulcan and Westaflex.

During the 1970s many gasworks closed down as natural gas was introduced. As oil prices climbed and natural gas prices remained relatively stable, the use of gas in industry and homes accelerated. From 1970, the various gasometers around Melbourne - at Tooronga, North Fitzroy, Essendon, Sandringham, Newport, Preston, Highett, Collingwood, Williamstown, Brighton, Footscray, Dandenong, Mentone and Heidelberg - were all demolished (Proudley 1987). Gasometers stored town gas at near atmospheric pressure and temperature. The centre chamber sat above a water tank, sealing the gas inside, and with no room for air inside, the holder prevented gas from igniting. The centre rose to accommodate more gas while maintaining constant pressure. By the 1980s, the only physical evidence of the Melbourne's extensive coal gas industry was a Regulating House in Macaulay Road, North Melbourne (Proudley 1987). The shift to articulated natural gas allowed the gas to be stored under high pressure within the network, with a regulator at each home. The benefit of this system is that the network provides both a transport medium, and a short term storage medium. This is in contrast to electrical supply that requires a constant dynamic match between supply and demand as electricity must be generated the instant it is consumed. In 1973, the Gas and Fuel Corporation took over the last private gas company in the state - the Colonial Gas Association - thereby becoming the monopoly gas supplier in Victoria (Productivity Commission 1995).

During the 1980's, flexible duct further evolved, and second generation compressible duct was introduced. The compressibility substantially reduced the volume of the finished product, reducing warehousing and transport requirements. A number of manufacturers produced a similar product, including, for example, Adbo, and Romet Industries, which used the trade name "Bonzaflex". The duct was manufactured by wrapping a wire helix, with glue, onto a cylindrical mandrel assembly that was composed of a pair of collapsible semi-circular components three metres long. This was followed by a sheet of cloth, which adhered to the wire, then a glass wool blanket, and finished with plastic sleeve to encompass the entire assembly. The collapsible mandrel assembly allowed the finished duct to be released from the assembly. The duct was susceptible to breakdown of the glue causing the wire to fall away from the fabric, and separation of the ends of the fabric. This resulted in collapse of the duct, particularly in the return air ductwork.

Shortly after, third generation duct was introduced, which was available from many suppliers and known generally as interlock duct. It consisted of three layers; the core, bulk insulation and sleeve, and was produced as a multistage process. The inner core was produced as a continuous process with a fabric or plastic film, with structure provided by an aluminium or plastic ribbed extrusion, which sometimes also included steel wire. The core was then wrapped with a glass wool blanket and encased in a polyethylene sleeve. Interlock duct is still available, but is not widely used in the residential market due to its higher cost.

By the late 1980's, glued duct was introduced, which was of similar construction, but which used solvent based adhesives to bond the core, and steel wire to maintain structure, and water based adhesives were introduced some years later. Ultrasonic welding was also introduced as an alternative means of constructing duct core. Flexible duct for the residential market is still produced using similar construction and processes, except that the Victorian residential market uses almost exclusively polyester fibre for bulk insulation, although glass wool is available, and widely used in other states. Polyester gained favour due to its low irritant and inert qualities. Most flexible duct currently produced for the Victorian residential market uses glued PET (polyethylene terephthalate) films with steel wire, polyester fibre and a polyethylene or metallised PET sleeve.

A number of further developments to the process of producing flexible duct have been proposed in Australia, but have not been commercialised (for example, Donnelly 2003a, 2008, Novaduct 2008).

Up until the 1980's, the Australian ducted heating industry had paralleled that of the North American market. However, beginning the early to mid 1980's, a number of manufacturers, began producing a range of plastic fittings, such as Vulcan with a plastic floor register boot in 1981 (Vulcan 1981). Other manufacturers, such as Genda Corporation started producing plastic fittings in the late 1980's. This included, for example, floor registers that were produced with injection moulded polycarbonate, ceiling diffusers using ABS (acrylonitrile butadiene styrene), branch take-offs (BTO's) produced with blow moulded polyethylene or polypropylene, among other products. While the steel BTO's were insulated with sprayed polyurethane, the plastic BTO's were mostly uninsulated due to the lower thermal conductivity of plastics.

There was initially significant resistance within the central heating industry to the use of plastics – metal products were considered superior and plastic was still considered sub-standard. However the significant cost advantage, coupled with the gradual realisation that plastic fittings offered some superior features, gradually led to the acceptance, and eventually, an almost complete take-over of the residential fittings market. Interestingly, the North American market has maintained its use of metal plenums, branches, grilles, registers and diffusers, although there has been some shift in recent years. A number of reasons have been identified, including reduced metal manufacturing costs due to economies of scale and access to cheaper labour, increased resistance to plastic components, difficulty in meeting fire standards across federal, state and local jurisdictions, and a market structure that is resistant to new and innovative entrants.

Until the early 2000's, virtually all of the plastic fittings had been produced locally. The high cost of tooling for plastic moulding in Australia had constrained the number of products on the market. However, the rise of East Asian manufacturing, in particular China, has meant that tooling costs are significantly cheaper, and with lower Chinese labour and business running costs, an expanded range of plastic grilles, registers and diffusers are now produced in China by a larger number of Australian distributors.

Although not obvious at the time, the shift to plastic BTO's may have contributed to significant efficiency improvements in ducted heating in Australia. The North American ducted market has been grappling with significant energy losses due to air leakage through leaks from fittings, and at duct–to-fitting joins. A significant amount of research has been conducted in North America, leading to standards for leakage, such as ASHRAE Standard 152 (Modera 2005), and California's Title 24, which requires mandatory leak testing of ducted systems (California Energy Commission 2005). Other jurisdictions, such as the UK, have included duct leakage measurement as a necessary component of HVAC performance in the context of reducing greenhouse emissions through improving energy efficiency (for example, Energy Performance of Buildings Directive 2008). There is evidence that Victorian systems utilizing flexible duct and plastic BTO's have significantly lower leakage than comparable North American systems.

Approximately 90 percent of Victoria's gas comes from the Esso/BHP Billiton production areas in the Gippsland Basin. The remainder comes from gas reserves in the Otway Basin, near and around Port Campbell in western Victoria. Further gas fields are also being developed in the Otway and Gippsland Basins, and in Bass Strait (Energy Networks Association 2007). Australia has much lower natural gas prices than Europe and the United States, and Victoria has the cheapest prices in Australia (Australian Energy Regulator 2007). Natural gas supply in the eastern states has been sheltered from global gas markets due to the requirement for gas to be delivered through pipelines, and the development of competitive markets has contributed to maintaining low residential natural gas prices (ABARE 2003). The natural gas usage cost is around a third of the cost of electricity usage. However there are a number of factors that are likely to put upward pressure on Victorian wholesale gas prices, which will feed into residential prices, in the medium to long term. These include the globalization of liquefied natural gas (LNG) trading, emissions trading, declining natural gas resources in Bass Strait with the need to supplement gas supply from the north of Australia or the north-west shelf via a trans-continental pipeline, increasing demand for gas for electricity generation, and the potential for increasing gas demand for transport.

2.2 Heating energy use in Victoria

Natural gas has had the largest share of total household energy supply in Victoria since the mid 1970's, and continues to easily represent the largest share of household energy supply. Electricity is the next largest, followed by wood and wood waste. Heating oil represented a significant share of energy from the mid 1960's, and was experiencing rapid growth, however the oil crises during the 1970's led to substantial price rises, leading to a shift away from oil heating. It is informative that the shift from oil heating was rapid, dropping from 17.5 PJ/annum in 1977 to 3.9 PJ/annum in 1982, representing an 88 percent decline over 5 years. Wood has maintained a large share of heating energy supply, but has shown a decline since 2002. Electricity demand growth has accelerated since 2000.

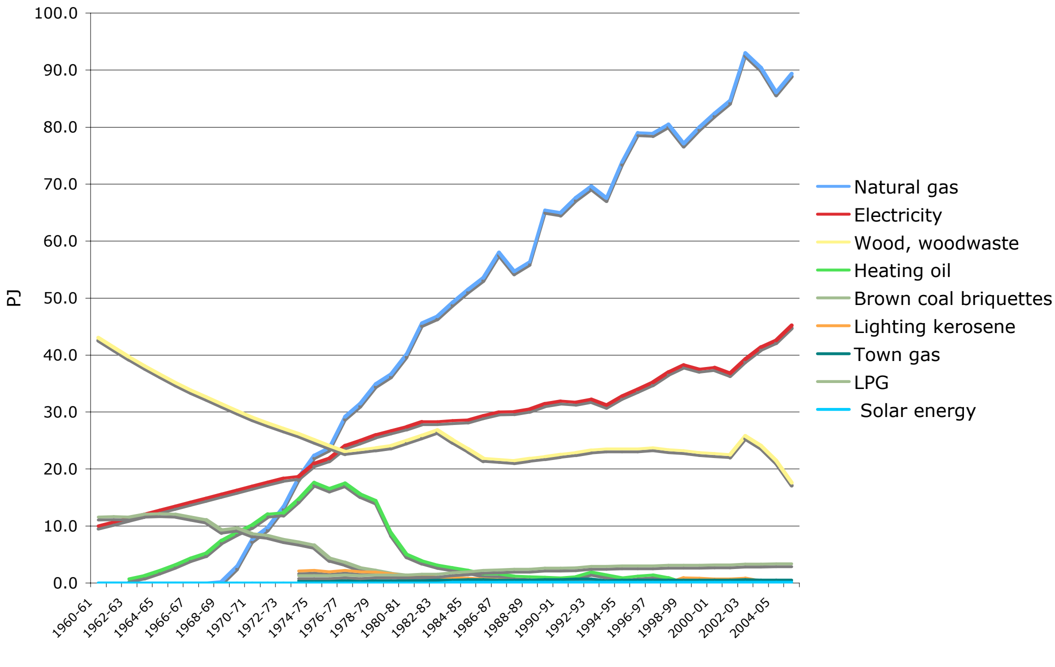


Figure 1 Victorian total annual residential energy use 1960 - 2005. Source: ABARE (2007)

Figure 2 graphs natural gas usage only, with the estimated share of ducted heating also shown, highlighting the close relationship between the growth of natural gas demand and ducted heating demand. The main residential use of natural gas in Victoria is for space heating (ducted and non-ducted), and hot water.

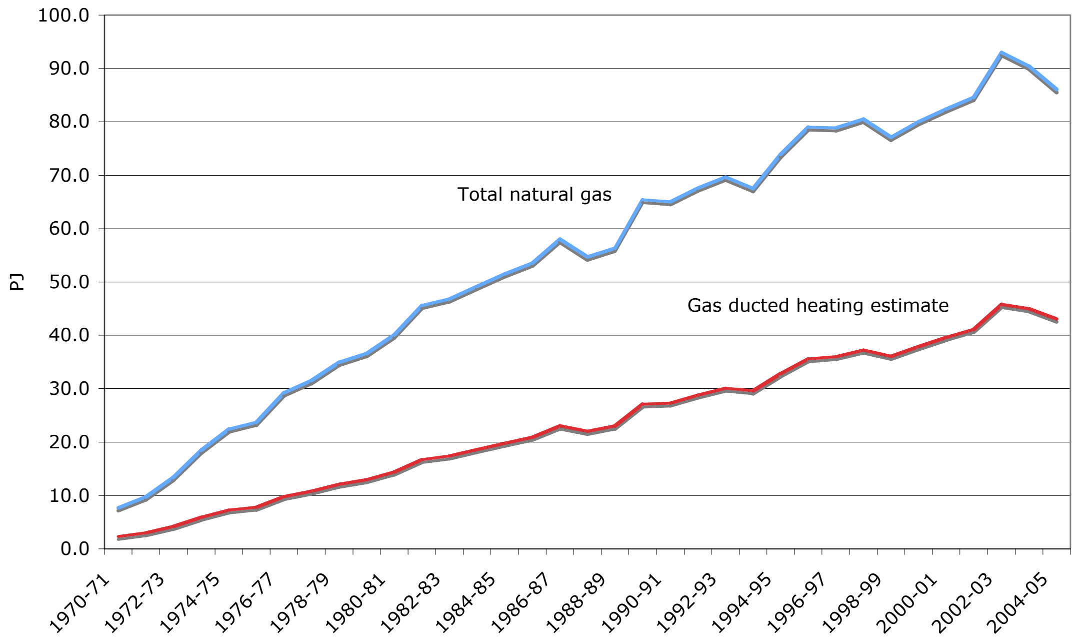


Figure 2 Victorian total annual residential natural gas use and gas ducted use 1972 - 2005 (PJ). Source: Calculated estimate for ducted and ABARE (2007).

2.3 Gas ducted furnace sales and existing stock

Table 1 provides an estimated summary of ducted and non-ducted gas heaters in Victoria. There are currently approximately 768,000 households using gas ducted heating as the main form of heating (ABS 2005a). Sales of ducted heating furnaces are composed of installations into new dwellings, conversion to gas ducted from another form of heating in existing dwellings, and replacement of existing furnaces. New installations and conversions will require the sale of ductwork, but replacement of furnace only will not require a change of the ductwork.

	Total household in Victoria	Estimated average household heating natural gas usage (GJ)	Estimated average furnace power (kW)	Estimated average hours of use	Estimated total energy consumption (PJ)	Estimated total greenhouse emissions (million tonnes CO_2-e)
Ducted	768,000	58	20	800	44.5	2.8
Non-ducted	632,000	29	10	800	18.3	1.2

Table 1 Summary of annual estimates for ducted and non-ducted gas space heaters in Victoria 2005. Sources: Calculated estimates, ABS 4602.0 (2005), Gas and Fuel Corporation (1990), AGO (2007)

According to an Essential Services Commission report (2007), Victorian gas distributors report that on average, three to four star ducted gas heating systems consume 50 to 56 GJ per annum, and that ducted gas heating uses slightly less than double the amount of gas than non-ducted heating, for an equivalent star rating.

Based on the growth in the proportion of households using gas ducted between 2002 and 2005 increasing from 35.8% to 40.1% (ABS 2005a), the annual growth of gas ducted heating calculates to 45,000 units per annum, and calculates to 40,000 units per annum between 1999 and 2002. For non-ducted gas heating, the same ABS data showed an increase of 2,000 units per annum between 1999 and 2002, and a decline of 14,000 units per annum between 2002 and 2005. The ABS data does not provide any indication as to what type of heating the non-ducted households switched to.

In 2006/7, there were 37,459 new dwellings in Victoria (ABS 2008). Anecdotal evidence suggests that a large proportion of new metropolitan detached homes have gas ducted heating installed as the main form of heating, with a lower proportion of units and townhouses electing to install gas ducted heating. According to an Essential Services Commission report (2007), the vast majority of new dwellings being connected to the gas network in Victoria have gas central heating, and distributors' report that the average annual consumption for a three star furnace is 56 GJ. The same report suggests that a reasonable assumption is that for new dwellings using ducted heating, 85 percent use a three star furnace.

The National Appliance and Equipment Energy Efficiency Committee (2004) provides an total estimate using BIS Shrapnel data of 50,000 units nationally, although they comment that the figure is probably understated. Industry sources suggest that the figure is closer to 55,000 units nationally. Victoria makes up an estimated 80 to 85 percent of the national central heating market, with most of the remaining sales in NSW and the ACT. At 85 percent of the market, Victorian sales are estimated at 47,000 units per annum. The ABS data and industry sources suggests that there has been some growth in the ducted market over the last decade but that the market is currently stable.

Given the market for new homes and conversions from other heating types, the market for replacement furnaces is estimated at around 15,000 to 20,000 units per annum, most of which are 3 star units. Assuming a calculated trend growth, it is estimated that there were approximately 560,000 systems in use 15 years ago. Taking the ABS estimate of 768,000 systems already installed in 2005, it is estimated that 78 percent of total systems were installed more than 15 years ago. Anecdotal evidence suggests that ductwork replacement is less common than furnace replacement, suggesting that probably two thirds of systems have ductwork that is more than 15 years old. These estimates suggests a very long changeover time for the existing furnaces and longer for ductwork which has implications for the efficiency and performance of the existing stock.

2.4 Comparison of energy prices

The average cost of natural gas provides the lowest cost purchased energy source for heating, together with firewood, if supplied at $150 per tonne, although gas can usually be burnt more efficiently, delivering a greater quantity of useful energy. The current Victorian gas tariff structure provides a three-step tariff, which declines with increasing gas usage. The tariff structure provides perverse incentives to the adoption of high efficiency equipment and ductwork, providing lower cost natural gas with increasing usage.

	Usual units	Price	cents/MJ
Natural gas	cents/MJ	1.0	1.0
Electricity - peak	cents/kWh	13.0	3.6
LPG – non transport	cents/MJ	3.0	3.0
Firewood - bulk	$/tonne	150 to 250	0.9 to 1.6
Firewood - bags	$/5 kg bag	5	6.3
Wood pellets	$/tonne	475	2.7
Brown coal briquettes	$ per 20 kg	13.50	3.0
Solar	N/A	0.0	0.0

Table 2 Approximate price of heating energy sources for residential customers in Melbourne 2007. Not including fixed or service charges.

Gas usage charge	Price (cents/MJ)
First 6000 MJ - peak period	1.2062
Next 3000 MJ - peak period	0.8800
Over 9000 MJ - peak period	0.6250
First 6000 MJ - off peak period	1.1213
Next 3000 MJ - off peak period	0.8078
Over 9000 MJ - off peak period	0.5927

Table 3 Natural gas tariff for residential customers in Melbourne, prices effective from 1 Jan 2008. Not including fixed and service charges. Source: Origin Energy 2008

2.5 Brief overview of heating types in Victoria

Natural gas ducted heating is the most common type of main heater in Victoria, with 40.1% of homes, and non-ducted natural gas is the second most common main heating type, with 33% of homes (ABS 2005a). Wood burners are common in non-metropolitan Victoria with 10%, with electric element heating representing 8%. In many cases, households will have other heaters, in addition to the main form of heater. This might include reverse cycle heat pumps, open fires, wood burners and fan heaters. The ABS data emphasizes the main form of hating, and does not provide guidance on the relative use of other heaters.

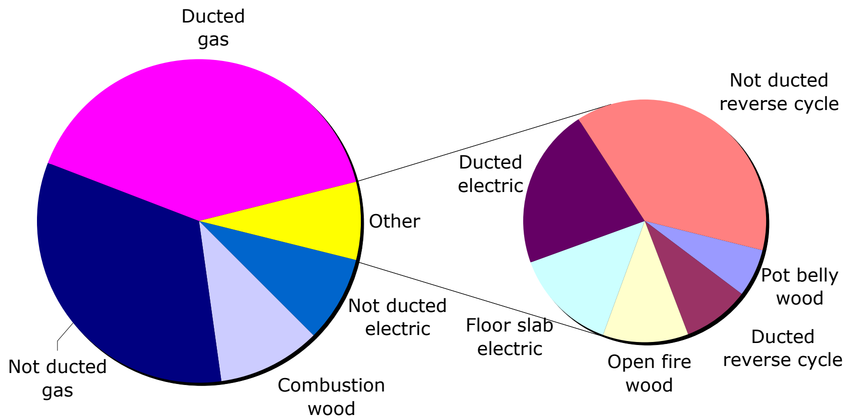


Figure 3 Main heater type in Victoria 2005. Source ABS (2005)

2.5.1 Natural gas ducted and non-ducted

Approximately three-quarters of Victorian homes using natural gas as the energy source as the main form of space heating (ABS 2005). From an energy efficiency perspective, the benefit of using gas for heating is that it is a primary energy source and can be burnt with minimal contribution to local pollution, at around 90% efficiency (for 5 star ducted furnaces and 95% for 5.5 star), incurring minimal gas distribution losses, while having the lowest greenhouse emission intensity of any of the fossil fuels. Gas heating has the benefit of a rapid start-up time before useful heat is produced.

Gas space heaters consist of flued and flueless types. When natural gas is burned, heat, water vapour and other gases, including carbon monoxide and nitrogen oxides are released. In flueless types, these gases are releases into the living space, which requires adequate ventilation to reduce occupant exposure. Both flued space heaters and ducted heaters release the combustion by-products external to the living space. Flued space heaters can be further divided into balanced and unbalanced types. Unbalanced flued draws air for combustion from the living space, creating a slight reduction in pressure, which draws outside air into the living space, whereas balanced flued draws combustion air from outside. Flueless space heaters also take the air required for combustion from the living space.

Non-ducted heaters are used to warm a living space up to 50 m^2, but can provide heat to a larger area if sufficient air movement allows, whereas ducted heaters can heat an entire home.

2.5.2 Electric reverse cycle

In recent years, there has been a substantial shift towards reverse cycle systems to provide winter heating and summer cooling. Although only 4 percent of Victorian households use reverse cycle heating as the main form of heating, 22 percent of Victorian households have a reverse cycle cooler installed (ABS 2005a). The cost difference of optioning reverse cycle heating, compared to a cooling only model, is usually relatively small, providing an incentive to purchase the heating option, even if it is not expected to be regularly used. The ABS data does not provide an indication of the frequency of use of reverse cycle heating when it is not the main form heating. Reverse cycle split systems are sometimes favoured by builders and contractors, due to the ease with which they can be installed, particularly if the building or block layout makes it difficult to install ductwork or a gas furnace. Additionally, the bulk store sales model has a strong bias towards selling equipment that can be immediately delivered. Bulk store sales staff don't usually have the training to design a ducted system, and prefer to refer the design to an experienced contractor if the consumer has a preference for a ducted system. Bulk stores now dominate the residential air conditioning market, and it is expected that reverse cycle units will continue to increase their market share of the cooling market (Australian Greenhouse Office 2004a).

When the coefficient-of-performance (COP) of reverse cycle heat pumps is taken into account, the running cost of high efficiency reverse cycle heating compares favourably with natural gas in moderate winter climates, with 5 star reverse cycle equipment operating at lower cost than natural gas heating. However, it remains more greenhouse intensive due to the reliance on brown coal for electricity generation in Victoria, with the high greenhouse intensity generation negating most of the efficiency gain in terms of greenhouse performance. In order to maximize the efficiency advantage of reverse cycle heat pumps, electricity needs to be sourced from low emission sources, such as wind, hydro or solar.

Reverse cycle systems have the benefit of also providing cooling in summer, however they contribute to peak electricity demand in summer, putting significant pressure on the generation and distribution network (George Wilkenfeld and Associates 2004b).

One of the drawbacks of wall mounted split units is the stratification inherent in blowing warm air from a single high position on a wall, which tends to reduce the effectiveness of the heating. Ducted reverse cycle systems tend to produce lower levels of stratification by improved distribution of the heated air, combined with regular air changes due to the constant running fan drawing air back to a return air grille.

Outside of the mains gas network, reverse cycle heat pumps may be a good financial option in regions having mild winters, however heat pumps operate with reduced performance at low outdoor temperatures, and are generally unsuitable in cold climates, with the COP dropping 30 to 40 percent at outdoor temperatures below $6^{o}C$ (Australian Greenhouse Office 2004b). This increases energy consumption, and reduces heating performance when it is most needed. Some equipment contains an evaporator defrost facility to de-ice the evaporator in cold conditions, and a backup electric resistance heater is available in some equipment. Both of these features allow a heat pump to provide reduced levels of heating in cold conditions, but at a substantially lower efficiency.

Ground source heat pumps, which use the earth to supply heat to the evaporator, overcome this problem in cold climates, and provide a higher COP. They are substantially more capital expensive due to the need to employ drilling or excavation equipment and install a piping system.

2.5.3 Wood

Although wood has declined in recent years, it still represents a significant share of the heating market in Victoria, most of which occurs in regions outside of the mains gas network. Todd (2008) claims that there are approximately 20,000 households per annum nationally that switch away from wood, to gas or electricity. In Victoria in 1999, there were 241,000 households using firewood as the main heating source, each averaging 4.3 tonne usage per annum, and 180,000 households using firewood as a secondary heat source, averaging 1.9 tonne per annum (Todd 2003).

Firewood usually represents a cheaper option than bottled LPG, depending on the local cost and availability of wood, and some householders have the opportunity to self-collect at low or no cost, particularly in rural regions. Todd (2006) provided an estimate of Victorian firewood costs in 2005 at \$140/tonne (collected from wood yard) and \$230 - \$250/tonne in Melbourne delivered. The greenhouse emission intensity of firewood can vary significantly depending on harvesting technique, forest type and other considerations (Australian Greenhouse Office 2003). Under certain wood supply conditions, with the use of high efficiency wood burners, firewood represents the among the lowest greenhouse intensity space heating. Wood heating can contribute to local pollution, particularly in urban areas, and the use of firewood raises a number of issues in addition to greenhouse emissions, including impacts on biodiversity and wildlife, and land degradation (Driscoll et al. 2000).

Open fireplaces are occasionally used for their radiant heat and aesthetic value in homes using gas ducted heating as the main source of heating. Fireplaces draw large quantities of air out of the living space and up the chimney, and for an average sized room of 40 m^3, it will take only 5 minutes to replace the full volume of air. This limits the efficiency, and may result in a net energy loss overall due to the use of the open fire (Todd 2003, 2008).

Wood pellet heating has experienced significant growth in parts of Europe and North America, but represents a small market share in Victoria. Unlike traditional wood burners, pellet heaters burn a processed wood product. The pellet delivery can be automated, and the burner control enables high efficiency, low pollution and low ash. Wood pellets, like firewood, may have the potential for low greenhouse intensity, but there is no published data on the greenhouse implications for pellet heating in Australia. The small number of pellet suppliers in Australia presents a challenge for pellet consumers in obtaining competitively priced pellets, and there is evidence that the pellet price has risen substantially in recent years - in 2006, pellets could be purchased at $360/tonne, but a recent review of prices showed a price of $475/tonne. At $475/tonne, and 80 percent efficiency, pellet heating is similarly priced to electric element heating, which is substantially more than reverse cycle. Pellet heating expansion in Victoria is constrained by the dilemma that consumers will only purchase burners and fuel if they are available at a competitive price, but new producers will not make the necessary investment unless they can be assured of sufficient demand. The expansion of the pellet heating market in Europe has benefited from the close proximity to burner and fuel suppliers throughout Europe, allowing markets to develop naturally once the critical mass of suppliers had been reached.

2.5.4 Hydronic

Natural gas fired hydronic heating represents a very small share of the market, in part due to its high capital cost. Although it performs similarly to a good quality gas ducted system in terms of energy delivered into the living space, advocates of hydronic heating claim that the use of radiant panels can provide an equivalent comfort level with a lower quantity of delivered energy. Hydronic systems generally have a significant radiant component to heating, but some systems also provide a substantial convective component.

Copper based systems perform better than steel based systems, and have the benefit of also providing domestic hot water, however the price of copper has risen significantly in recent years, and the cost of employing copper is typically 50 percent higher than steel.

In regions outside of the mains gas network, solar boosted hydronic heating using evacuated tube collectors, assisted with bottled LPG or firewood, can provide lower energy costs and lower greenhouse emissions, but incurs substantial capital costs. Depending on the system, hot water may also be incorporated into the system.

In-slab hydronic systems can provide very good thermal comfort, with the floor providing radiant heat over a large surface area. The main drawback to in-slab heating is the long time lag when starting the system due to the large thermal mass, and the equally long delay when stopping the system, which can result in overshooting the temperature when the daytime conditions improve. In cold climates, which require constant heating, the time lags are less important, but Victoria's moderate climate (with the exception of the Alpine regions) is generally unsuitable for in-slab radiant heating systems.

2.5.5 Electric

There are various types of electric resistance heaters, including bar radiators, fan heaters, convection heaters, oil filled bar heaters, in-slab resistance element floor heating, convective panel and radiant panel heaters. Except for in-slab heating, which will lose some energy to the ground, their efficiency can be taken as 100% given that they are contained within the living space and that all energy they consume will degrade to heat within the living space, including fan power. Small bar radiators with a 1 to 2 kW capacity can be purchased at discount stores for as little as ten dollars. The use of electricity in Victoria results in high running costs relative to many alternatives, and have a high greenhouse emission intensity. They are not usually recommended other than as short term heaters for small areas.

2.5.6 LPG space heaters

LPG fired wall or room heaters provide a convenient form of heating in regions outside of the mains gas network, and are frequently used as a supplementary form of heating in place of firewood. Bottled LPG is similarly priced to electricity, both of which are often more expensive than firewood, but bottles must be refilled or changed-over regularly.

2.5.7 Heating types summary

Heating type	COP/ Efficiency(1)	Greenhouse emissions (kg CO_2-e/MJ delivered heating)	Energy cost (cents/MJ delivered heating)	Approx. capital cost ($/kW)(2)
Ducted natural gas 4 star, 10% ductwork losses	0.72	0.09	1.39	175
Ducted natural gas 5 star, 10% ductwork losses	0.81	0.08	1.23	200
Ducted natural gas 5.5 star, 10% ductwork losses	0.86	0.07	1.17	215
Ducted natural gas – typical 20 year old system, 2 star, 30% ductwork losses	0.49	0.13	2.04	N/A
Fan heater/element heater	1.00 (3)	0.37	3.61	10
Firewood – potbelly	0.40 (4)	0.07 (5)	2.34	100
Firewood - open fire	0.10 (4)	0.28 (5)	9.38	-
Firewood – slow combustion insert	0.60 (4)	0.05 (5)	1.56	200
Ground source reverse cycle heat pump, direct expansion	5.80 (6)	0.07	0.62	800 (7)
Hydronic - natural gas boiler	0.72 (10)	0.09	1.39	500 (11)
LPG space heater	0.85	0.15	3.53	50
Oil filled electric heater	1.00 (3)	0.37	3.61	40
Reverse cycle split - 2 star	2.40 (12)	0.15	1.50	260
Reverse cycle split - 4 star	3.25 (12)	0.11	1.11	300
Reverse cycle split - 5 star	3.80 (12)	0.10	0.95	320
Solar/LPG hydronic - 60% solar fraction	0.85	0.06	1.41	1700 (13)
Solar air heater	-	0.00	0.00	2100 (14)
Wood pellet heater	0.80 (15)	- (16)	3.29 (17)	400 (15)

Table 4 Comparison of Victorian space heating sources compared for heating energy delivered into the living space. Energy costs from table 2. Greenhouse factors source: AGO Greenhouse calculator (2007) and Australian Greenhouse Office (2003).

Notes (1) The COP/efficiency refers to the energy efficiency at the appliance, not the primary energy efficiency. In the case of electricity, there may be significant losses in the generation and delivery of the energy (2) Capital cost based on average complete system including installation (3) All element and fan power will degrade to heat (4) Source: Australian Greenhouse Office (2003) (5) Assume woodland : 0.1 kg CO_2-e/kWh. Can vary significantly depending on type and harvest technique (6) Source: Earth to Air Systems 2008 (7) Costs dependant on drilling/excavation (10) Assume boiler efficiency 80% and distribution losses of 10% (11) Assumes steel cores - the use of copper will increase costs typically 40% - 50% (12) COP figures are based on AS/NZS 3823 test conditions – COP reduces at lower outdoor temperatures (13) Total capital cost based on Harris (2006), assume 20 kW capacity (14) Based on the Sun Lizard (Sun Lizard 2008) (15) Wood Pellets Australia (2008) (16) Data not available (17) Assume 18 MJ/kg

2.6 Energy efficiency barriers

Energy efficiency first emerged as an Australian policy issue in the 1970s, initially because of concerns about energy scarcity and depletion of energy reserves, and exacerbated by the oil shocks of the 1970s. More recently, energy efficiency has re-emerged because of the drive to lower greenhouse emissions (Productivity Commission 2005). Pears (2007a) claims that energy efficiency can deliver greenhouse reductions at low or negative, net cost, and deliver reduced energy bills to householders. He suggests that energy efficiency needs to be mainstreamed, and that Australia needs incentives to encourage individuals to act.

There are significant opportunities for low-cost reductions in emissions across the Australian economy through the deployment of existing technologies and practices, including energy efficiency and fuel switching in homes (Garnaut 2008). However, there are broadly two types of market failure that inhibit the take-up of higher efficiency practices in residential heating. One relates to externalities in the supply of information and skills. The other involves a principal–agent (or split incentive) problem, where the party that makes a decision is not driven by the same considerations as another party who is affected by it.

Householders may only make decisions about the options available for improving the thermal comfort of their home a handful of times during their life, limiting their experience, and even where they have access to sufficient information, they may make decisions that appear personally suboptimal for reasons of ‘bounded rationality’. Bounded rationality is the concept that people may not be able to always make perfect or optimum decisions, as their knowledge and processing abilities are limited. In some cases, even where people have access to information, the personal costs of gathering and analysing the information may exceed the perceived benefits, leading to the choice to remain uninformed, even where they have the opportunity to make choices that may be advantageous in the long term (Garnaut 2008). In many situations, people will make decisions that will are sufficient to their needs, rather than optimal, based on limits to their personal time, attention and other resources. People will tend to use rules-of thumb, and favour the maintenance of the status-quo, rather than shift to more energy efficient choices.

While there is ample information available for householders to choose within heating groups, such as comparing the star ratings of gas ducted furnaces, it is difficult for a householders to choose between different heater groups. For example, reverse cycle heat pumps can be compared for star labels, but the star label system does not allow the direct comparison between, say, gas heating and electric heating. Where a householder chooses a ducted system, there is no readily accessible, objective information available to choose between different types of ductwork, other than the general consideration that a higher thermal R-value will be better. Householders have no reasonable way to ascertain that they have been supplied ductwork of a specified thermal rating or quality, and rely on the goodwill of the contractor. Given that ductwork is installed out of sight, there is a lack of awareness of its quality, performance or whether it requires maintenance over time.

In choosing a heating solution, there is an asymmetry between retailers, developers, builders or contractors, and householders, which can lead to a number of consequences. Firstly, householders only have the opportunity to purchase products or services that are available from the seller. For example, there tends to be demarcations between suppliers of gas and reverse cycle, wood heaters, solar heaters, insulation products and energy efficiency services. Secondly, sellers may favour products that they prefer to sell, rather than options that may be optimal for the householder – retailers, developers, builders and contractors do not have to pay the energy bills. Examples include products that have better sales margins, preferences for a particular type of system and brand, and ease of installation. In many cases, a lack of training in energy efficiency may reduce the value of a seller's advice, even when it is offered in good faith – for example, the efficiency of reverse cycle heat pumps is sometimes promoted as an energy efficient feature, without an awareness of the high greenhouse emissions and costs of electricity in Victoria relative to other heating options, such as natural gas and wood. Thirdly, a heating retailer will usually be expert at selling and installing heating equipment, but other options, such as replacing ductwork, installing insulation, window treatments, door sealing or other options, will not usually be considered as part of the "thermal comfort solution".

When householders do consider future energy use, there is often a tendency towards adopting high rates of discounting on future costs, providing a bias towards lower-efficiency choices. In some cases, householders may be giving consideration to selling their home in coming years, reducing the incentive to purchase products with higher capital costs but lower lifetime costs. In other cases, budget limitations may restrict choices, even where there is a preference to making purchase decisions that would provide lower lifetime costs.

A further impediment to reducing energy consumption is the preference for warmer indoor temperatures during winter. Shove (2007) contends that nowadays people prefer an indoor temperature several degrees higher than fifteen years ago, and that expectations for comfort and convenience have been gradually ratcheting upward. These expectations are reflected in many aspects of living, including thermal comfort. The expectation of simply raising the thermostat on the heating control has become embedded in lifestyle choices, compared to, say, putting on a jumper when it gets cool.

An impediment towards the adoption of energy efficient heating is acute in rental properties. This is an example of the split incentive problem, occurring between landlords and tenants, where landlords have a preference for low capital cost equipment and fit outs, while tenants are required to pay the running costs of heating equipment. An Australian Bureau of Statistics survey in South Australian confirmed that renters generally use lower efficiency, and higher operating cost heating appliances (ABS 2005b).

One of the challenges in improving the uptake of higher efficiency ductwork has been that AS/NZS 4254 does not require labelling on ductwork, despite there being agreement within the duct industry that labelling should be introduced. The mandatory labelling of ductwork would allow building surveyors to inspect ductwork, and assist interested parties to randomly check product. The Australian Competition and Consumer Commission has already indicated that labelling of product would make it easier to enforce the Trade Practices Act, as incorrect labelling could be construed as false or misleading (Australian Competition and Consumer Commission 2006). While the Building Code of Australia should provide minimum requirements for ductwork, only a small proportion of installations are required to comply with the BCA, and there is frequently a failure to comply when it is required.

3. Regulatory requirements for duct

3.1 Building Code of Australia

The regulatory requirements in Victoria for duct are defined by the Building Code of Australia - 2007 (Australian Building Codes Board 2007) for new homes and renovations, and the Plumbing Code of Australia - 2004 (National Plumbing Regulators Forum 2004) for installations into existing homes. The relevant sections are Section J.5 in the BCA and Section E in the PCA. There have been a number of changes to the minimum thermal standards in the BCA over recent years. Both the BCA and PCA reference the main Australian Standard for ductwork, AS/NZS 4254.

The objective of the energy efficiency measures in the BCA is to reduce greenhouse gas emissions by more efficient use of energy. The standards for buildings are intended to eliminate worst practice, thereby reducing greenhouse gas emissions, while avoiding excessive technical and commercial risks and unreasonable costs (ABS 2003). The BCA is generally taken as "best practice" in the residential heating industry, where there is no inducement or encouragement to optionally adopt higher standards.

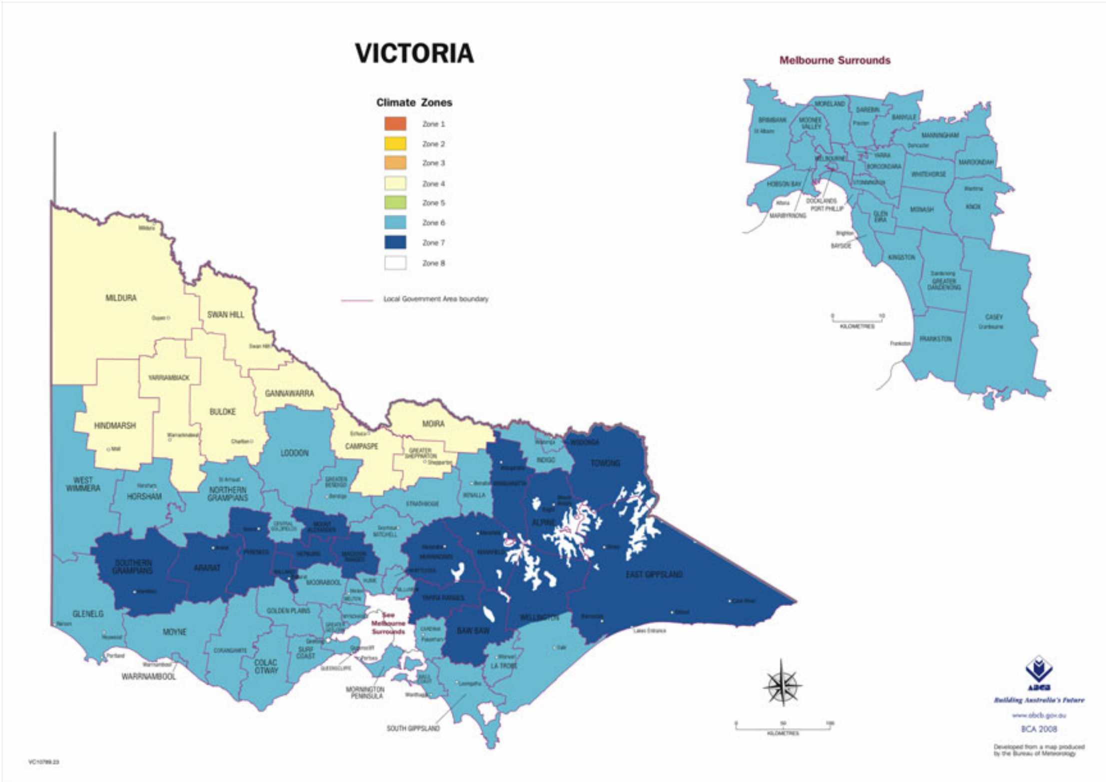


Figure 4. ABCB climate zone map for Victoria. Source Australian Building Codes Board 2007

	Zones 4, 6 and 7 (all regions except for Alpine)	**Zone 8 (Alpine regions)**
Under enclosed suspended floors	1.0	1.5
Roof spaces	1.0	1.5
Fittings	0.1	0.1

Table 5 Required R-Value for ducting as it applies to gas ducted heating systems in established residential dwellings. Source: Plumbing Industry Commission 2005

	Zones 4, 6 and 7 (all regions except for Alpine)	**Zone 8 (Alpine regions)**
Under suspended floors without enclosed perimeter	1.0	1.5
Under enclosed suspended floors with enclosed perimeter		
Roof spaces where roof insulation is less than R0.5		
Roof spaces with sarking of greater than R0.5		
Fittings	0.4	0.4

Table 6 Required R-Value for ducting as it applies to gas ducted heating systems in new residential dwellings - Specification J5.2. Source: Building Codes Australia 2007

The lack of mandated labelling of flexible duct has allowed non-conforming product to be installed without it being recognized by building surveyors. The residential ducted heating and cooling market has traditionally emphasised the use of higher thermal rating duct and insulated fittings for cooling systems, in part because of the tendency for condensation to form on ductwork that are insufficiently insulated in cooling systems. From an energy reduction viewpoint, the temperature difference between the duct airflow and ambient conditions is greater in gas heating systems than refrigerated cooling systems, but this has often been neglected by the industry.

Table 12 provides an estimate of the proportion of sales by thermal rating for 150 mm flexible duct. The size was chosen because 150 mm duct is used primarily for heating, and most residential heating systems will use some 150 mm duct. It therefore provides an indication of the relative proportions of the thermal ratings of heating systems. A study wasn't undertaken to ascertain the correct proportion of thermal rating, however anecdotal industry evidence suggests that a significant quantity of R0.6 m^2.K/W product is being installed where regulations call for greater than R0.6 m^2.K/W.

The “Training needs Analysis” workshop, as part of the National Framework for Energy Efficiency, identified a number of hindrances towards the adoption of the correct product, including lack of knowledge of the relevant regulations, cost pressures, lack of regulation enforcement and lack of understanding (Sustainability Victoria 2005).

Duct size (mm)	Thermal rating	Estimated proportion of sales
150	R0.6	85 to 90%
	R1.0	10 to 15%
	R1.5	0 to 2%

Table 7 Estimated proportion of sales of 150mm flexible duct by thermal rating in Victoria. Source: Industry sources

3.2 Australian Duct Manufacturers Alliance

An industry body, the Australian Duct Manufacturers Alliance (ADMA) has been recently been formed is response to concerns expressed by the Australian Greenhouse Office (AGO) and the Australian Competition and Consumer Commission (ACCC). The industry body grew out of the Heating and Cooling Association, a sub-committee within the Master Plumbers and Mechanical Services Association of Australia (MPMSAA). ADMA represents flexible duct manufacturers, insulation manufacturers and assemblers across Australia with the view to establishing a self-regulatory system to ensure that flexible duct meets the relevant standards. The author is currently serving on the committee.

3.3 Fire standards

AS/NZS 4254 requires two sets of fire tests, AS/NZS 1530.3, which provides an index on ignitability, spread of flame, heat evolved, and smoke developed, and UL181.9, which provides a burning test. The AS/NZS 1530.3 indices constitute the four indices quoted on duct data sheets.

The North American market references UL181, using a wider range of tests, which include flame, burning and smoke tests. The tests discourage the use of plastic fittings, and polyester fibre bulk insulation.

In the Australian context, there is no evidence that ductwork causes fires, but may contribute to spreading a fire by acting as a conduit (Metropolitan Fire Brigade 2002). The main contributors to fires relating to central heating are a lack of maintenance of heater units, a restriction of airflow in the return air duct caused mainly by a build up of dust on the return air grille, or a build-up of dust on the fan.

4. Theory and modelling

4.1 Overview of energy losses

In gas ducted heating systems, air is drawn through return air duct by a blower fan, heated by the gas furnace, then delivered to the house via supply ducts to grilles or registers. Ideally, all of the energy released by the natural gas is imparted to the airflow, and then delivered to the living space. However, losses occur in the furnace and ductwork. Under steady state conditions, the energy delivered into the living space equals the energy lost through the building fabric. Energy is also absorbed and released through the thermal mass of the furnace, ductwork, building fabric, and building contents. This energy exchange represents transient energy transfer, and is more difficult to measure and model, and the field study did not include a transient energy analysis. The electricity consumed by the fan is also delivered to the airflow, both as the fan absorbed energy, and the electrical and magnetic winding losses of the motor if the motor is installed within the airflow. This energy is a net contributor to heating, however in a cooling system, this power contribution leads to a reduction in system performance. As such, there can be a benefit in specifying smaller ductwork, despite the need to increase fan power, if the decrease in thermal losses resulting from smaller ductwork outweighs the costs of the additional electrical power, both in terms of financial costs and greenhouse emissions.

A number of parameters associated with duct were assessed to provide supporting information for the field study. These include:

1. A discussion of the geometric properties of flexible duct, and its effect on the thermal resistance of duct.
2. An assessment of the energy life cycle of insulation to determine whether there is a trade-off between the additional embodied energy of insulation versus the energy savings.
3. A financial life cycle assessment of the energy savings of using additional insulation versus the additional capital cost.
4. An exploration of the current and future cost of natural gas, including a brief review of the upcoming emissions trading scheme.

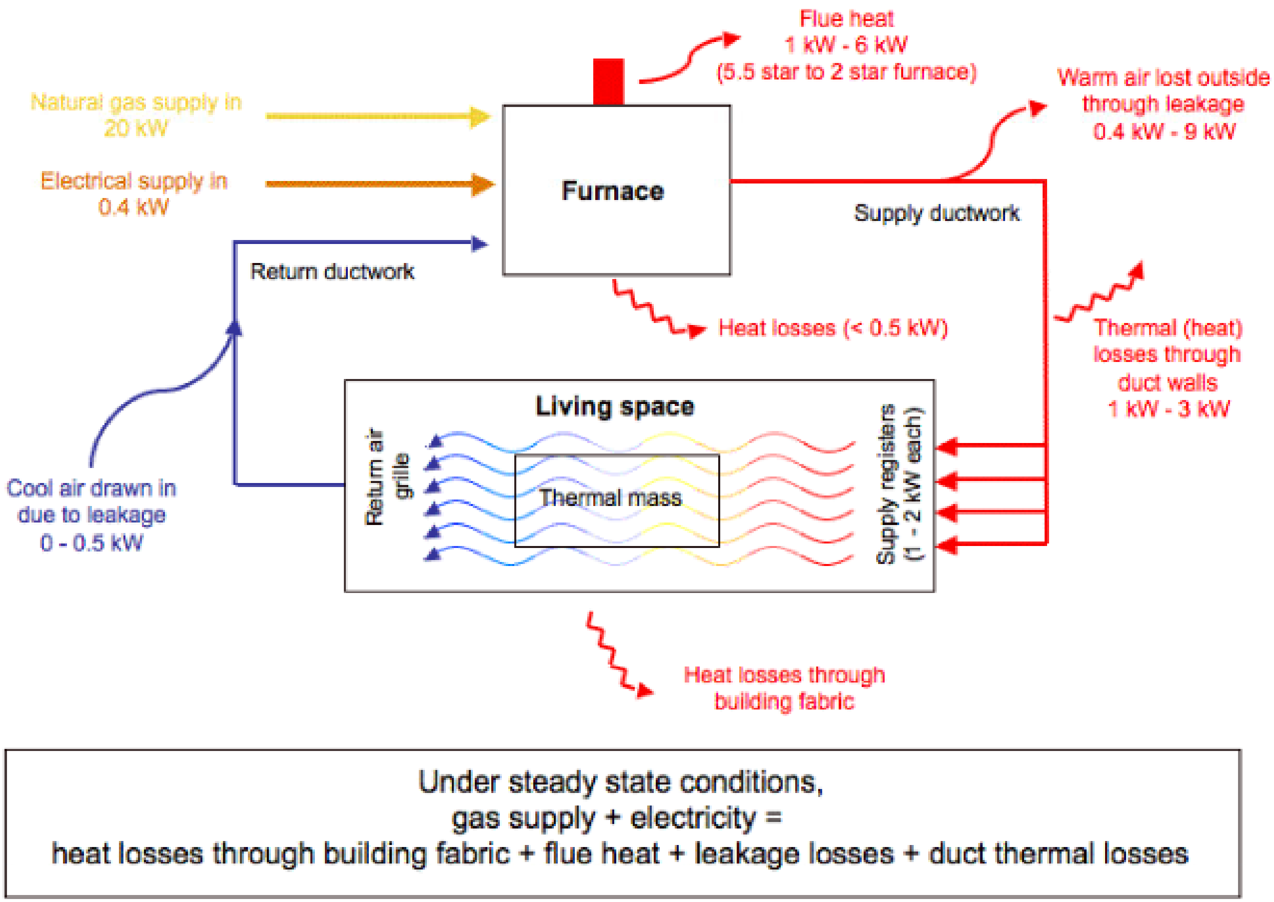


Figure 5 Typical gas ducted heating system diagram overview. Source: field study results

4.1 Effective thermal resistance of insulated duct

Bulk insulation is measured and supplied with a flat-form thermal resistance defined in AS/NZS 4859 using the guarded hot plate test. The thermal resistance is measured by sandwiching the insulation between 2 plates, one of which is heated. The steady state heat that passes through the insulation is measured, and determines the R-Value. When that blanket is wrapped around a duct, the effective thermal resistance is reduced (or conduction increased), because the outer layer provides a larger surface area for surface convection and radiation to occur. For example, if a 150mm duct is wrapped with 50mm thickness blanket, the resulting complete duct has an outside diameter of 200mm. The following equation from Levinson et al. (2000) describes the resulting thermal resistance;

$$\frac{R_f}{R_{flat}} = \frac{\ln(1+(t/r_i))}{t/r_i} \quad (1)$$

where
R_f is the duct annular thermal resistance
$R_{f,flat}$ is the flat-form (slab-form) thermal resistance
t is the insulation thickness
r_i is the inner radius (or duct core)

Plotting the equation for a number of core diameters and insulation thicknesses yields the following graph.

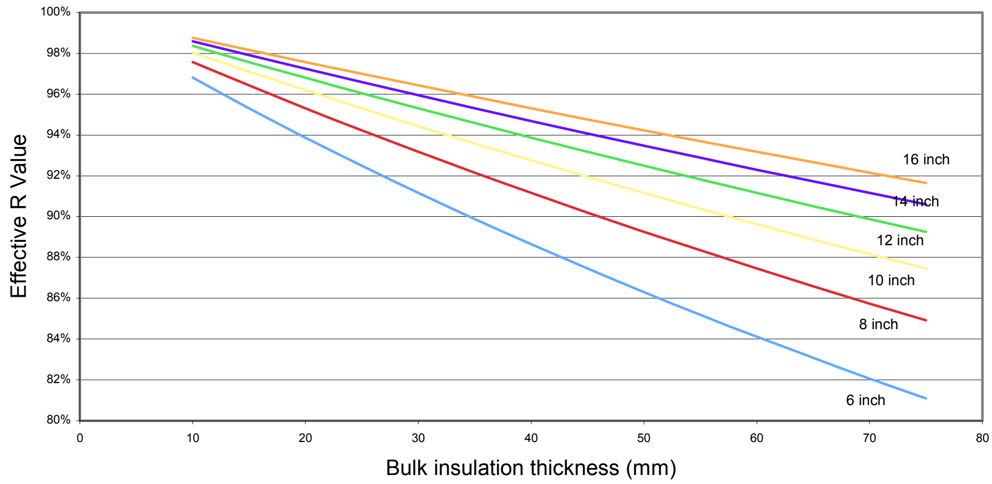


Figure 6 Effective annular thermal resistance versus thickness of bulk insulation

The graph shows the derating required for flat-form R-Value when the insulation is wrapped around a duct. For example, for 150mm duct, with 50mm thick bulk insulation, the effective thermal resistance will be 0.86 times the flat-form R-Value – so R1.0 becomes R0.86. It shows that the effect is most prominent for smaller duct sizes, and increase almost linearly for increasing thickness.

The manufacture of polyester fibre involves a number of trade-offs between maximising thermal resistance and reducing the cost of manufacture. Variables include, among others, mass of the blanket, loft, thickness, proportion of recycled fibre, proportion of hollow fibre, denier of fibre and proportion of low-melt fibre. In order to maximise the thermal resistance in annular form, compared to slab-form will necessarily include taking account of the thickness. The table may also have implications in the choice of bulk insulation, where, for example, glasswool can obtain the same thermal resistance as polyester, but with reduced thickness.

Duct has been insulated with either glass wool or polyester blanket, and has been specified according to the slab-form thermal resistance value. This still applies in the North American market, which utilises glass wool blanket. The Australian Building Codes Board (ABCB) defines the minimum thermal resistance for ductwork in the Building Code of Australia (BCA). In recent years, the ABCB has been strengthening efficiency codes for building products, and has increased the required thermal resistance for ductwork. The ABCB defines the R-Value of duct as the Rt – or total R-Value, including thermal resistance provided by bulk insulation, duct materials and air films. The BCA has provided an allowance of R0.15 for the air films and surfaces (BCA 2008 - Part 3.12.5.3 explanatory information item 4), thereby implying that, for example, the use of R0.85 blanket will provide a thermal rating of R1.0 when the R0.15 allowance is added.

Outer air film	0.15
Sleeve	0.01
Bulk insulation	Typ. 0.4 to 1.5
Core	0.01
Inner air film	0
Total	**Typ. 0.42 to 1.72**

Table 8 Typical thermal resistance of components of insulated duct.

4.2 Life cycle energy analysis of bulk insulation

Life cycle analysis is a means of assessing the impact of a product over its lifetime. It typically includes an assessment of the manufacture, installation, use, decommissioning, and disposal. The use of insulation in buildings and building products usually involves choices about the costs and benefits of their use. The analysis will typically include a financial analysis, but may be expanded to include other parameters, such as greenhouse emissions, energy use and resource use. The use of insulation follows the law of diminishing returns where increasing the insulation beyond a certain point results in little additional benefit, and many studies have been conducted to evaluate the effectiveness of wall and ceiling insulation to arrive at an optimum level of insulation (for example Treloar et al. 2000, Hasan 1999, Papadopoulos and Giama, 2006). In the residential heating market, the required level of insulation for ductwork is determined by the Building Code of Australia or the relevant plumbing standards. A brief analysis was carried out to ascertain whether there is an optimum level of duct insulation to minimise life cycle energy consumption, and minimise life cycle cost.

In order to assess the relative merit of replacing a ducting system, and the life cycle costs of providing additional insulation, a standard ducted heating system was defined as consisting of 8 outlets, 20 kW furnace with 80% efficiency and 34 m^2 of ductwork and fittings (the area relates the total internal core area of the system). This consists of 36 metres of 150mm duct, 9 metres of 200mm, 6 metres of 250mm and 6 metres of 300mm. The assessment was done for three grades of polyester insulation, R0.6, R1.0 and R1.5 at 230, 350 and 450 grams/m^2 respectively.

It was assumed that the above system consumes 58 GJ per annum with R0.6 ductwork, and that the equivalent R1.0 and R1.5 systems will consume approximately 46 GJ and 37 GJ per annum respectively. It was assumed that the furnace operated for 800 hours, giving an average hourly consumption of 72 MJ, 58 MJ and 46 MJ respectively.

Embodied energy data can vary between sources, but typical values are provided by Baird et al. (1997) for a number of insulating materials.

Material	Embodied energy (MJ/kg)
Cellulose	3.3
Glass wool	30.3
Polyester	53.7
Polystyrene	117
Wool (recycled)	14.6

Table 9 Embodied energy of various insulating materials. Source: Baird et al. (1997).

Taking the total mass of polyester fibre for the typical system at 8, 12 and 15 kg for R0.6, R1.0 and R1.5 respectively, gives total polyester fibre insulation embodied energy of 414, 630 and 810 MJ respectively. The difference represents around 6 to 18 days of furnace energy consumption, and is therefore three orders of magnitude below the expected total lifetime energy use of the system. As such, the energy expended in the production of insulation has no significance in respect of making a choice about the insulating material, or quantity, at the level of thermal resistance used in ducted heating systems. If any of the commonly used bulk insulation materials were used, the results would have a similarly low level of significance.

4.3 Optimum level of insulation to minimise lifetime cost

In order to derive an expression to minimise the lifetime cost of flexible duct, it is necessary firstly to derive equations for the cost of purchasing duct, and the cost of energy losses. Flexible duct is generally produced in size increment of 50 millimetres, starting at 150 mm, although other sizes may also be produced.

Flexible duct is a commodity product in Melbourne, and therefore the selling price usually bears a close fixed relationship to the manufacturing costs. Based on the known construction materials, techniques and industry data, the retail price per metre squared of standard, silver sleeve, polyester fibre duct in Melbourne in April 2008, including GST, has been approximated using regression analysis, by the expression:

$$Cost = A(2.86 + 9.51R) \qquad (2)$$

where
A = area of duct (internal core) (m^2)
R = thermal resistance of duct (m^2.K/W)

The area of the duct refers to the internal core area, so for example, a 6 metre length of 150mm duct is 2.8 m^2. Table 5 shows the calculated cost of a range of sizes and thermal ratings based on equation 1. The equation is not intended to provide an exact cost, but to provide a representative cost to enable a quantitative analysis of the total lifetime cost of providing more or less insulation.

	Duct size (mm)				
R-Value	150	200	250	300	350
R0.6	24.61	32.81	41.01	49.21	57.42
R1.0	35.53	47.37	59.21	71.06	82.90
R1.5	49.18	65.58	81.97	98.36	114.76

Table 10 Indicative retail price, including GST, of various sizes and thermal ratings, of flexible duct using equation 1.

The lifetime cost of energy loss is related to the internal area of the core for the entire system, the temperature difference between the inside of the duct and the surroundings, the hours that the system is used, the price of energy, the thermal resistance of the duct and the projected life of the system by the expression:

$$Cost_{energy\_loss} = \frac{0.0036 A \Delta t HPL}{R} \qquad (3)$$

where
Cost = lifetime cost in dollars
A = total (internal) duct area (m^2)
$\triangle t$ = difference in temp. between inside of duct and ambient (^oC)
H = annual hours of operation (hours)
P = price of gas ($/MJ)
L = projected life of system (years)
R = R value of duct ($m^2.K/W$)

Now in order to find the thermal rating of the ducted heating system that will minimise the lifetime cost, we take the cost of the duct plus the cost of the energy that is lost due to the thermal losses attributed to the duct:

$$Cost_{lifetime} = Cost_{energy\_loss} + Cost_{capital} \qquad (4)$$

giving

$$Cost_{lifetime} = \frac{0.0036 A \Delta t HPL}{R} + A(2.81 + 10.5R) \qquad (5)$$

and graphing this expression for a given set of conditions,

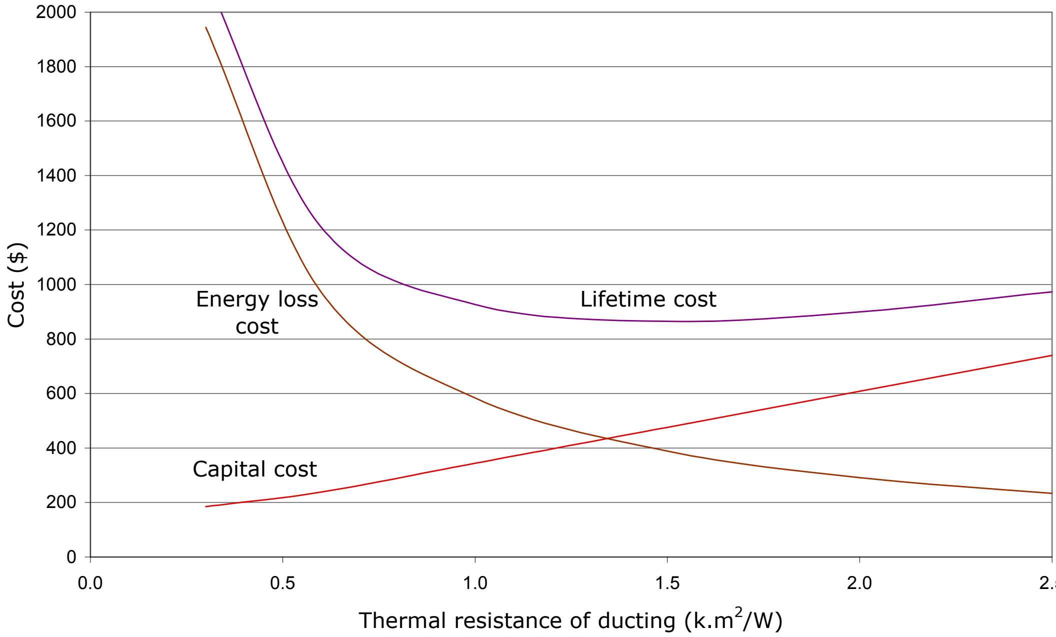


Figure 7 Calculation of optimum R value to minimise lifetime cost. The above graph shows duct cost and energy loss cost only – excludes fittings and installation costs - is for a typical 8 outlet system with 34 m^2 of ductwork, lifetime of 15 years, gas at 1 cent/MJ, △t of 45 ^{o}C and 800 hours of use per annum.

Figure 3 shows the cost of duct and energy loss cost only. The labour and installation cost for duct with different thermal resistance is assumed to be the same. It is assumed that insulated fittings will be used regardless of the type of duct. Fittings are only available with one level of insulation, which is usually taken as R0.4. The fittings constitute a very small proportion of duct surface area, and therefore contribute a small proportion of thermal energy loss.

In practice, all systems will be different, and the optimum R Value will depend on the individual parameters. However, generally, the capital cost of the duct increases linearly with the thermal resistance, but the energy loss cost asymptotes towards zero cost. From a lifetime financial cost perspective, there is little disadvantage in installing duct with a higher thermal resistance, and given that the parameters will be generally unknown, there is less risk in adopting a higher thermal resistance, although it results in a higher initial outlay.

There are practical constraints to the maximum R value that can be used with ductwork. Firstly, the size of the duct becomes larger as the R value is increased, and secondly, building members, including posi-struts and pre-fabricated roof frames provide an upper limit on the size of ductwork. These factors tend to limit the practical R value using polyester fibre to R1.5, and less in some cases. Glass wool provides an opportunity to increase the R value slightly for a given physical size.

Differentiating equation 5 with respect to R, and equating to zero, and solving for R will give the optimum R to minimise lifetime cost for the given conditions.

Setting

$$0 = \frac{d}{dR}\mathrm{Cost}_{\mathrm{lifetime}} \tag{6}$$

and solving gives

$$\mathrm{R}_{\mathrm{optimum}} = \sqrt{\frac{0.0036\Delta \mathrm{tHPL}}{10.5}} \tag{7}$$

for insulated, polyester fibre, flexible duct, with silver sleeve in Melbourne based on costs as at April 2008, ignoring the net present value of expenditures.

A number of important points arise from equation 7. Firstly, the parameter A – area – is not present, indicating the overall size of the duct area has no bearing on the optimum R value, although it will impact on the overall energy loss. A doubling in any of the parameters Δt, H, P and L (being temperature difference, annual usage, price of gas and lifetime of system) individually will increase the optimum R value by a factor of 1.4. The constant, 10.5, is a function of the price of duct. A doubling in the price of duct will reduce the optimum R value by a factor of 0.7. This constant can be scaled according the appropriate price being charged from equation 1 if manufacturer, distributor or retailer prices vary. Table 5 compares the optimum thermal rating for various gas costs and lifetimes. As is evident from the table, an increase in either parameter increases the optimum thermal rating.

	Gas cost (cents/MJ)						
Lifetime		**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
	5	0.6	0.8	1.0	1.1	1.2	1.4
	10	0.8	1.1	1.4	1.6	1.8	1.9
	15	1.0	1.4	1.7	1.9	2.2	2.4
	20	1.1	1.6	1.9	2.2	2.5	2.7

Table 11 Comparison of optimum R to minimise lifetime cost for various gas prices and lifetimes where $\triangle t$ of 45 ^{o}C and 800 hours of use per annum.

4.4 Residential gas costs discussion

The cost of natural gas may influence householder choice of heating type, performance, usage patterns and other factors related to energy use. Victoria has very low residential natural gas prices, but there is evidence that there a number of factors that are likely to put upward pressure on prices in the medium to long term.

Natural gas is delivered via pipelines, which provide logistical and geographical constraints to gas trading. However the advent of tankers shipping LNG worldwide provides the opportunity for international trading of gas, regardless of proximity to pipelines, or the natural gas source. At one level, this may increase competition between suppliers, providing reduced costs to purchasers. However the strong global growth in demand for natural gas, coupled with declining reserves in many countries, has provided an opportunity for suppliers to sell to the highest bidder. The experience of Western Australia is that the establishment of liquefied natural gas (LNG) trading has increased price pressures on locally supplied gas.

Although a number of countries have had similar prices to Australia, in recent years, there have been significant price pressures, due to a combination of declining supply combined with strong demand. In recent decades, both the UK and USA, like Australia, have maintained relatively low natural gas prices due to substantial indigenous resources. However both have experienced sharp increases in recent years due to a combination of declining supply and strong demand, and the need to supplement indigenous resources with imported natural gas and liquefied natural gas (LNG). The UK became a natural gas exporter following the development of the North Sea oil and gas fields from the 1970's, but since the late 1990's, production of oil and natural gas has plateaued, and is now declining. The UK is now a net importer of natural gas, and by 2010, gas imports could be meeting up to a third or more of the UK's total annual gas demand, potentially rising to around 80% by 2020 on the basis of existing policies (UK Department of Trade and Industry 2007).

Similarly in the USA, natural gas had been promoted as an inexpensive, clean fuel, but strong demand growth, combined with declining production, has forced prices upwards. U.S. natural gas production is projected to decline annually by about 0.5 percent, with LNG imports augmenting supply, and increasing substantially over the next decade (California Energy Commission 2007).

The globalization of supplies means that the price being paid in one part of the world may be affected by the demand in other parts of the world, and in some cases, the natural gas price may be pegged to the crude oil price. For example, most of the gas in Germany and the Netherlands is secured from Russia on long-term contracts that are priced relative to oil (Dey 2008). In a tight LPG market, buyers can bid the spot price upwards, even after the tankers have left their port of origin. For example, the UK has been supplementing indigenous reserves with LNG to help smooth winter heating demand, but is being regularly outbid, with the available LNG being shipped elsewhere (Dey 2008). The growth in the globalization of natural gas is reflected in the growth of LNG tankers – globally, there are currently 258 LNG tankers in circulation, and there are now 129 new ones on order, waiting to be delivered (Macdonald Smith 2008).

According to Dickson and Noble (2003), a northern supply option for natural gas may be required in the Australian eastern states somewhere between 2012 and 2020. They suggest that a significant infrastructure investment will be required in the medium term to increase supply. This may necessitate the building of a transcontinental pipeline, from Australia's north (from Papua New Guinea or the Timor Sea) or from the North West Shelf, although Roarty (2008) suggests that coal seam gas developments in Queensland and New South Wales may defer the need for these pipeline projects. Further Bass Strait developments will provide security of supply, including the Turrum Project, which is expected to supply gas from 2015, and the Kipper Project, which is expected to supply gas from 2011 (ABC PM 2008).

The concept of a transcontinental pipeline goes back to the early 1970's when the Federal minister for minerals and energy, Rex Connor, promoted the idea. More recently, former Western Australia premier Dr Geoff Gallop raised the matter with the Prime Minister, Premiers and Chief Ministers. He suggested that the pipeline would bring many benefits, including choice, competition and energy security (Gallop 2005). Short et al. (2003) suggests that the quantity of gas to be sold that would make the necessary transcontinental infrastructure investment profitable ranges from 100 to 200 petajoules a year (or between 9 and 18 per cent of the projected market size in 2020).

Wilson (2007) claims that the current gas prices in the eastern states discourage investment in gas supply, and that a substantial investment to increase supply will require an increase in gas prices. He suggests that the current prices are well below global market rates and that there is a likelihood that the eastern states will become more exposed to market prices in the future. Garnaut (2008) suggests that prices will rise rapidly towards export parity, and remain at that level over the longer term. Most of the gas developments in Western Australia have been based on the LNG market, where the wholesale price is four to five times higher than the domestic market. There are currently no LNG exports from the eastern states, however the development of gas liquefaction plants using natural gas or coal seam methane may begin to expose Victoria to global gas markets. For example Santos has proposed a plant in Gladstone, Queensland for export markets (ABC 2007).

Natural gas is often promoted a bridging fossil fuel for electricity generation, providing a lower emission alternative to black and brown coal (Diesendorf 2007). Given that Australia has abundant gas and coal reserves, but declining oil reserves, there may be increasing interest in the development of substitute transport fuels based on natural gas and coal over coming years, including compressed natural gas (CNG) and liquefied natural gas (LNG), which have a lower greenhouse intensity than petrol and diesel.

These factors are likely to put upward pressure on wholesale gas prices. Residential retail price rises will be tempered by the costs already associated with distribution, and retail costs and margins. For example, a doubling of the wholesale price of natural gas may lead to an approximate 30% increase to householders.

	Percentage of retail cost
Gas supply and transport costs to city gate	30
Local distribution and metering costs	60
Retailing costs - billing etc.	8
Retail margin	2

Table 12 Retail cost breakdown of natural gas. Source: IPART (2001)

4.5 Emissions trading scheme

Australia is due to introduce an emissions trading scheme (ETS) in 2010 (Garnaut 2008, Australian Department of Climate Change 2008). In a fully functioning ETS, the price of emissions will be set by the ETS market and will be based on the quantity of permits issued relative to the demand for permits, although the initial price may be capped by the Federal Government during the introduction period of the system. At the writing of this report, it is not possible to accurately predict the price of emissions, however an indicative price of \$20/tonne CO_2-e has been suggested in the early years of the system (Australian Department of Climate Change 2008). The purpose of the ETS is to reduce greenhouse emissions, however Pears (2008) suggests that the likely range of price signals sent by an ETS is unlikely to significantly shift people's behaviour. He suggests that other measures, such as energy efficiency programs and a mandatory renewable energy scheme will also be required.

As of 2000, excluding land use changes, and including the six principle greenhouse gases (CO_2, CH_4, N_2O, PFC, HFC, SF6), Australia is the fifth highest per capita emitter of greenhouse gases with 25.8 tonne CO_2-e per person annually, ranking first of the industrialized countries, and ranks sixteenth of all countries in total country emissions with 495 Mt CO_2-e per annum (World Resources Institute 2008).

The preferred position of the Government is that obligations for emissions related to natural gas for residential users would be applied to natural gas retailers and gas producers. For LPG, obligations would apply to producers, marketers, distributors and importers of LPG. For electricity supplied to residential customers, obligations would vary depending on the type of generation, but generally apply to the black or brown coal suppliers, or electricity generators.

From a residential customers' point of view, there will be no requirement to directly purchase permits, but there will be an increase in their utility energy usage cost, which may vary from billing period to period, with the emission component proportion being expected to generally increase over time.

Figure 8 provides an indication of the impact of emissions trading on electricity, natural gas, LPG and firewood retail prices, with solar included for reference. The graph has been derived by adding the cost of CO_2-e to the current Victorian retail price of energy sources, based on emission intensities derived from the Australian Greenhouse Office greenhouse factors worksheet (Australian Greenhouse Office 2007). The graph does not have a time component, and the generation and production costs are expected to vary in the future. The graph assumes that there will be complete pass through of the cost of emissions, from the producer to the retail level. The choice of the scale from zero to \$60 is somewhat arbitrary, and assumes that the cost will be well below \$60 in the short to medium term, although this is subject to uncertainties. The ETS Green Paper estimates that the price increase of energy will be 16 percent for electricity and 9 percent for natural gas based on a \$20 per tonne/CO_2-e permit price (Australian Department of Climate Change 2008).

The graph indicates that electricity has both the highest absolute cost of energy of the main heating energy sources (petrol has a similar cost, but isn't generally used for space heating in Victoria), as well as the highest rate of increase for a given emissions cost. The graph assumes the current generation mix for electricity for Victoria will be maintained, however the impact of the ETS will increase the uptake of lower emission intensity electricity sources, especially natural gas and wind in the short term (Garnaut 2008). These primary sources have lower emission intensities with a lower emission cost, but at a higher cost of production.

The trade-off between higher production costs and lower emission costs will be worked through over many years, and is an essential part of the transformation of energy supply in the future. The carbon price/energy cost curve for electricity under these circumstances is likely to show a flatter gradient while rising in absolute terms.

As can be seen from the graph, natural gas fares well in a carbon constrained environment, although, the price of natural gas is expected to rise due to factors other than the direct cost of emissions.

Agriculture is not expected to be included in the initial scheme, in part because of the difficulty in measurement and monitoring (Garnaut 2008). Although wood can perform very well from an emissions viewpoint in some situations, there is significant variability in emission intensities, and in some cases, the burning of firewood can achieve a net reduction in greenhouse emissions relative to letting the wood naturally break down in a forest (Australian Greenhouse Office 2003). As a sub-category of biomass, the preferred position of the Government is to apply a “zero rating” (Australian Department of Climate Change 2008), meaning that there will be no emission obligations associated with firewood, although activities associated with harvesting firewood, such as transport, will affect the consumer price. In theory, large upstream wood processors could be included into the ETS, although determination of the actual intensity may be challenging. The large number of small point sources for wood would probably lie outside of the scheme, and it would be difficult to regulate the collection and burning of firewood, particularly in rural regions.

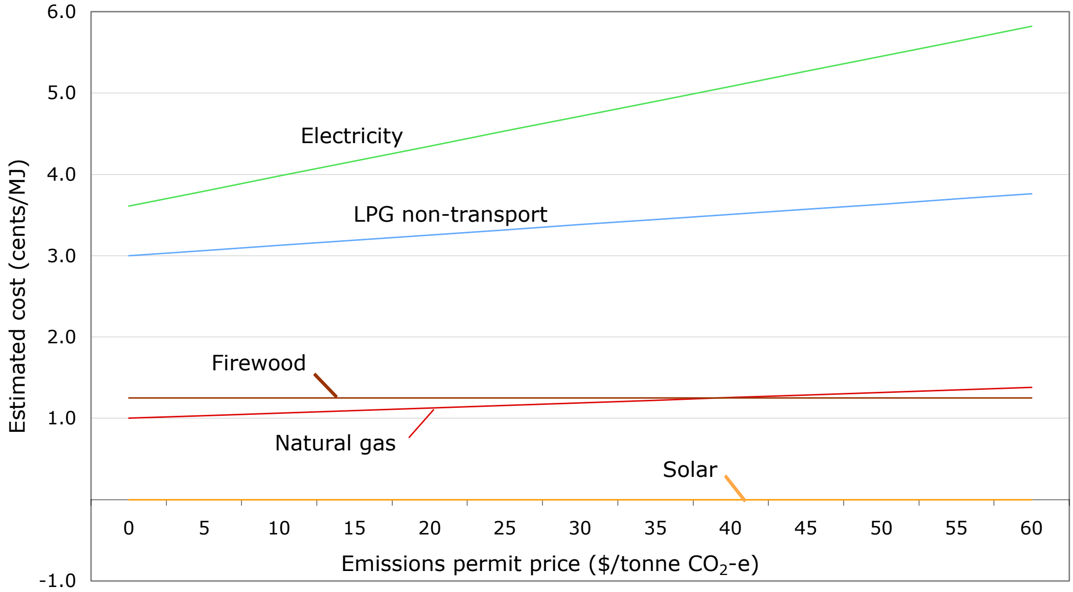


Figure 8 Estimated impact of a carbon price on heating energy source residential prices based on adding price of CO_2-e to current average retail prices, assuming complete pass-through of carbon costs. Not including fixed or service charges. Electricity based on peak price of 13 cents/kWh, natural gas averaged at 1 cent/MJ, firewood at $200/tonne, LPG at 3 cents/MJ, solar at zero. Greenhouse factors source: Australian Greenhouse Office (2007)

5. Field study

5.1 Field study overview

According to Andrews (2003), in the United States, forced air ducted systems typically lose 25% to 40% of the energy output, and that leakage and conductive losses contribute comparable amounts. According to Boe (1998), in research also conducted in the United States, losses range from 10% to 40%, with 30% being typical. Boe (1998) concluded that repairs and improvements to the duct system could be cost effective when the system components are accessible, and that there is significant scope to improve the efficiency of ducted systems.

Australian systems are comparable, but have some important differences, which will impact on the energy losses. However there has been no published data related to local systems, although there has been acknowledgement that Australian systems may be subject to similar losses to North American systems (for example Pears 1998a, 1998b, Energy Efficient Strategies 2008).

In forced air distribution systems, air is drawn through return air duct by a blower fan, heated or cooled as appropriate, then delivered to the house via supply ducts to grilles. Typically, the blower fan is just upstream of the heating or cooling components. Ideally, all of the energy imparted to the airflow is delivered to the living space, but losses occur in the ductwork, and are mainly due to air leaks and conduction losses (Francisco et el. 1998). Delivery efficiency is defined as the fraction of energy provided by the appliance that actually gets delivered by the ductwork, whereas the distribution efficiency is defined as the fraction of the supplied energy that actually goes to satisfying the load of the house (Francisco et el. 1998). The subtle difference is due to the fact that some of the energy losses can be regained through conduction or airflow, from unconditioned spaces to conditioned spaces. In most households, the distribution and delivery efficiencies will be almost the same.

There has been a substantial amount of research in the United States, and particularly in California, on ductwork performance, most of which has focused on leakage. Leakage occurs mostly around the duct to collar interface, and the collar to plenum interface, in residential systems (Sherman 2002). There is also the potential for leaks from plenums and other fittings. Australian systems differ to comparable systems in the United States and Canada in the type of distribution components used, and there is no comparable data available on residential duct system performance in Australia. Australia makes use of plastic branch-take-offs, instead of sheet metal based plenums. The flexible duct is of a similar construction type to that used in Australia, except that the United States uses mostly glass wool to provide the bulk insulation, whereas Victorian residential systems use mostly polyester fibre.

The measurement of delivery efficiency or distribution efficiency is difficult in situ. The most successful method is the coheat method, which measures the distribution efficiency directly. The test is conducted by installing an electric space heater in each living area, then cycling both the existing ducted system and the test system in turn. Typically, each system will cycle for around 2 hours, and each system will attempt to maintain a constant temperature. The energy consumption of both systems are compared, with the difference in energy consumption being attributed to duct losses. This system requires a sophisticated measurement and feedback system to ensure accurate control of the electric space heating system.

A number of related field studies have been conducted in North America. Francisco et al. (1998) measured the performance of eight homes with gas ducted heating in Washington State with the aim of comparing measured results with modelled results. Treidler and Modera (1994) conducted a field study on four homes in Maryland, with the aim of examining the potential for distribution efficiency. A study by Jump et al. (1996) consisted of sealing and insulating the duct systems in 24 homes in California, and comparing the data before and after the retrofits.

According to Modera (2005), duct leakage creates uncontrolled airflows with consequences that include low-pressure zones, increased infiltration that can increase or decrease humidity, non-uniform temperatures, and energy/capacity losses for the heating system.

The field study consisted of three components:

1. Conduct a field study in ten homes with ducted heating systems which are at least ten years old, including a measurement of thermal and leakage losses attributable to ductwork, followed by the replacement of the ductwork, followed by a re-assessment of the thermal and leakage losses to ascertain the improvement, if any. The household field study was the main component of the study.
2. Development of a thermal test rig to dynamically measure the thermal resistance of flexible duct to examine and validate the expected R-Values encountered in practice.
3. Development of a pressure test rig to ascertain the air leakage in the ductwork use in Victorian ducted heating systems.

The main component of the field study was the field testing of 10 households. The testing program involved:

1. Contacting the householder and visiting the home to conduct an initial assessment.
2. Arranging another visit to conduct testing of the gas ducted heating system including:
    a. Conducting a leakage test of the system, to ascertain the leakage efficiency.
    b. Running the heater and measuring the temperature and airflow at the supply outlets, after waiting for the system to reach steady state.
    c. Measuring the gas flow using the utility gas meter.
    d. Measuring the temperature at the return air inlet and furnace outlet under the house.
    e. Doing a visual inspection of the ducting under the house.
3. Drawing a duct system plan.
4. Arranging for replacement of the ductwork by a professional installer.
5. Retesting the system following step 2 above.

5.2 Apparatus

Chauvin Arnoux CA824 thermo-anemometer
Hanna HI-875I calibrated thermometer
Energy Conservatory Duct Blaster
Energy Conservatory DG-700 pressure gauge

5.3 Procedure

The duct leakage test used a kit that was imported from the United States, the Energy Conservatory "Duct Blaster". The kit consists of a fan with duct attached, pressure gauge, fan controller, and accessories. The duct leakage test ascertains the approximate combined volume of warm air that is lost *from* the supply ductwork to the outside, and the cool air, which is drawn *into* the return air ductwork. The energy loss due to supply air leakage is more significant because there is a greater temperature difference between the supply air and the outside, compared to the return air and the outside. For example, the air in the supply ductwork will typically be 40 to 60^{o}C, whereas the return air ductwork will typically be 15 to 22^{o}C. The kit is unable to distinguish between the airflows, however it is assumed that most of the losses occur through the supply ductwork because this constitutes significantly more duct area.

The test is conducted by firstly by sealing off all supply registers. Duct tape was taped over the floor registers, and where possible, the floor register flow damper was shut. In theory, there may be a small airflow behind the floor register, between the floor boot and the register flange. No attempt was made to prevent this potential leakage as this airflow represents leakage to the outside in normal operation.

Figure 9 Floor register sealed with duct tape, with tube inserted, which is connected to the pressure gauge to measure pressure within duct system.

The Duct Blaster fan assembly is then connected to the return air grille. The fan assembly has a length of duct with an adaptor fitted to the end. The adaptor is placed over the return air grille, and sealed with duct tape, and the entire return air grille is completely sealed. In some installations, the return air is fitted to a wall or door, with the return air passing through an open space or cupboard. With this configuration, the Duct Blaster duct was connected directly to the return air duct, as there would be air passing through gaps or openings in the door or cavity. When the Duct Blaster fan is operating, the fan blows air through the return air grille, and into the duct system. With the supply registers sealed off, the system should pressurise, and the only airflow into the system should be air leakage out of the ductwork. In order to measure the pressure within the system, a length of tube is placed into one of the supply registers, and sealed. The tube is connected to the pressure gauge, and the pressure gauge will measure the pressure difference between the inside of the home, and the duct system.

Figure 10 Duct Blaster fan connected to return air grille before grille is completely sealed.

At least one door is opened to ensure that the inside pressure is equalized to the outside pressure. Once the connections have been made, the fan is turned on and the speed slowly raised using the fan controller. The fan is set so that the pressure difference between the inside of the home and the duct system is 25 Pa. The choice of pressure is defined by ANSI/ASHRAE Standard 152-2004 (ASHRAE 2004)

While maintaining the fan, the volumetric flow rate through the fan is measured by connecting a tube to the pitot tube connection on the fan assembly. The Duct Blaster provides a conversion chart to convert the pressure drop across the fan to a volumetric flow rate. This flow rate represents the duct system leakage at a pressure of 25 Pa. The flow rate is taken as the estimated system leakage, although the actual leakage will vary. In practice, the pressure throughout different parts of the system is different, with the greatest level of pressure differentials occurring near the furnace ductwork. Given that the pressure test does not differentiate between supply and return leaks, the effect on system performance will vary from system to system, even where the leakage test result is similar.

The temperature of the outgoing airflow from the supply registers was measured using a calibrated thermometer with a probe attachment. The probe was inserted into the register and measured at approximately 100mm from the top of the register. The measurement was taken in the register to avoid inaccuracies resulting from the mixing of living space air with supply air.

The preferred method to measure the flow rate from the registers was flow hood measurement, however it was deemed insufficiently reliable and accurate. According to Walker and Wray (2003), flow hoods can be inadequate to measure airflows in residential systems, and can lead to large measurement discrepancies, although it is possible to obtain reasonable results under certain conditions. The difficulty with measuring the airflow is that there is inconsistent airflow across the register, and the airflow can be turbulent. Additionally, interfering with the airflow can alter the flow characteristics.

The method used in the field study consisted of taking the air velocity at various points on the register using an anemometer, estimating the average velocity, then multiplying by the outlet area to obtain the volumetric flow rate. The flows were inserted into a spreadsheet and an iterative process performed to match the total supply airflow with the estimated furnace output minus estimated leakage. This method allows a good approximation of the system. The flow rate was multiplied by the temperature to obtain the power of the incoming airflows according to the equation:

$$P = \dot{m}Cp\Delta t \quad (8)$$

where
P = power delivered (J s^{-1} or watts)
m = mass flow of air (kg s^{-1})
Cp = specific heat capacity of air (J.kg^{-1}.K^{-1})
Δt = difference in temperature between supply output and return air input (oC)

During furnace operation, the gas meter was observed to determine the gas flow rate of the equipment. Residential gas meters measure the flow rate in metres cubed per hour, which is scaled for conversion to mega joules. The meters were observed for one complete revolution of the minor dial, which was 0.5 or 0.6 m^3, and which took approximately one minute. Based on the energy consumed over a measured period of time, the power of the appliance was determined, and listed in table 21. Also shown is the calculated hours of operation, which is taken as the total annual consumption divided by the furnace power.

The householders' gas bills were noted, and are shown in figure 20. Only some bills were available, however the gas bills provide a summary of the previous twelve months usage, providing a minimum of twelve months data. The annual usage cycle is clearly evident, with the winter peak occurring in the August bill. Also apparent is the correlation of households over different years, indicating a varying heating load, caused by cooler days.

5.4 Results

Figure 11 provides a summary of gas usage attributable to space heating. Some of the homes used gas for water heating, and all the homes had a gas cooking appliance. The proportion attributable to space heating was estimated by analysing the seasonal usage patterns, and deducting the proportion attributable to water heating and cooking.

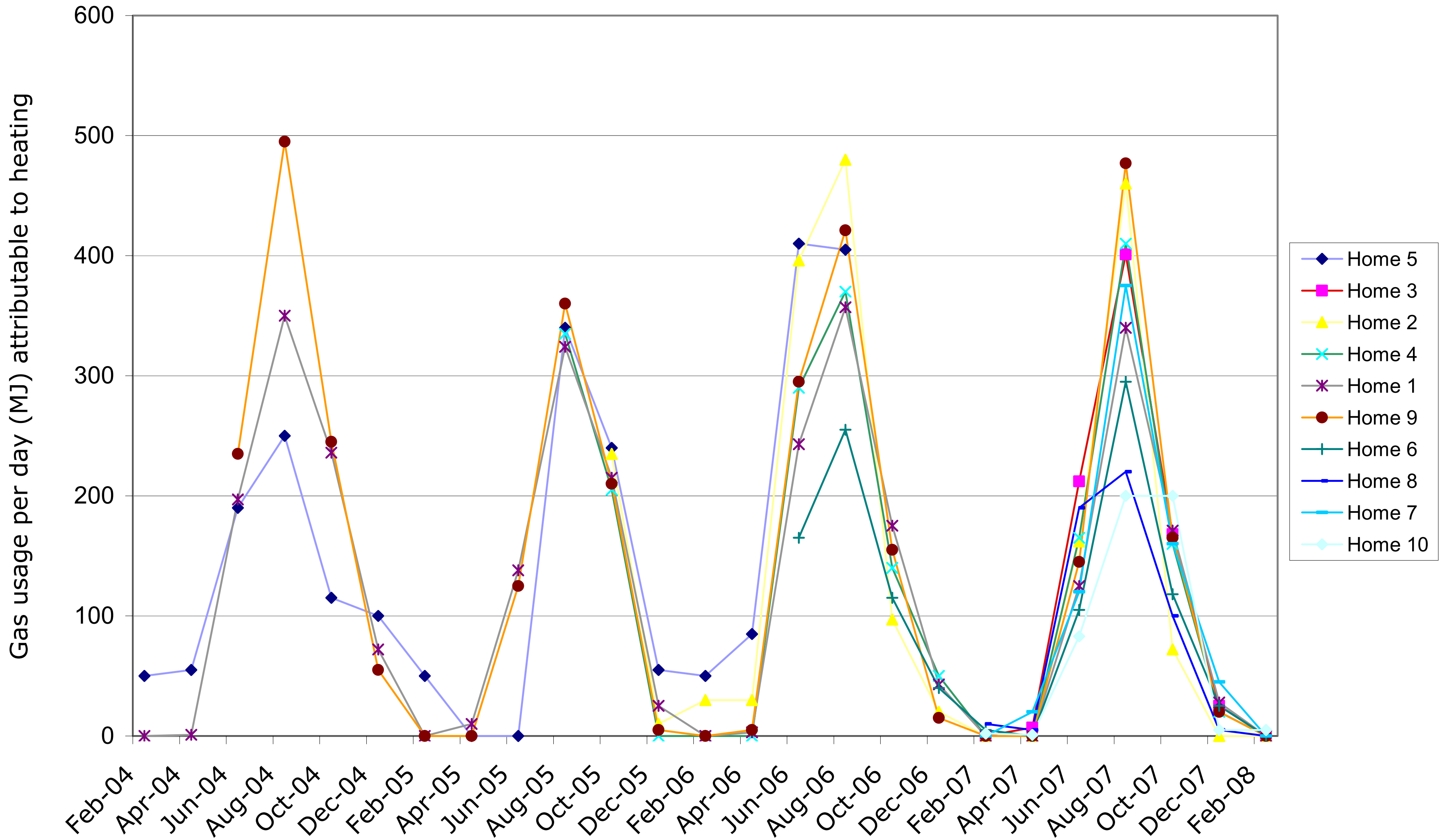


Figure 11 Gas consumption attributable to heating. Source: field study household gas bills

Typical taped join on a 20 year old system. If the tape has been pulled tightly, the join remains intact although the end of the tape may have loosened.

Many older systems have duct sleeve that has deteriorated, and sleeve has broken down.

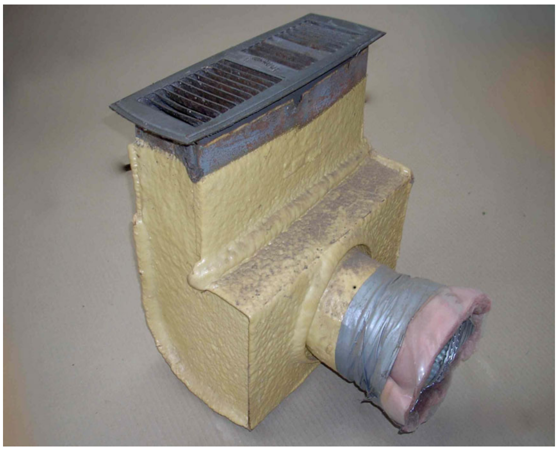
Taped join where two lengths of duct have been joined. Duct tape hasn't been pulled sufficiently tight and hasn't been wrapped several turns, and tape has fallen away.

Supply plenum typical of that used in the 1970's and early to mid 1980's. Entry 14" duct is on the left, with several 6" outlets at the front and sides.

Figure 12 Field study duct examples

Crushed supply and return air duct next to furnace. Duct is semi-rigid aluminium, which doesn’t spring back when pushed. Also visible is the broken outer sleeve, resulting in substantial leakage. The householder suggested that the duct may have been crushed by a dog.

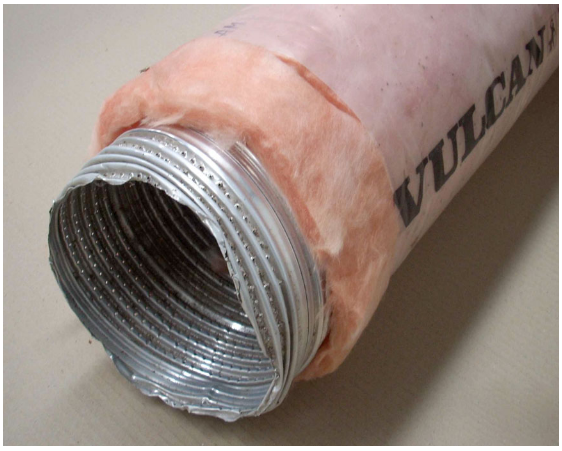
Starting collar in a floor mounted return air box. The gaps between the tabs allow leakage into the return air duct from under the house.



Floor register and boot typical of that used older systems, which worked well except for occasional holes in the sheet metal resulting in leakage.

Plenum typical of that used in older systems. All supply duct was connected to a central plenum which supplied all outlets.

Figure 13 Field study duct examples



First generation flexible duct, available from the early 1970's to mid 1980's. This example is Vulcan "Sidewinder". The perforated holes are visible. Although not obvious from the photo, the duct is rigid and non-compressible, but can be bent. Uses glass wool and polyethylene sleeve.

Second generation flexible duct produced from the early 1980's, similar to "Bonzaflex" style. This example has disintegrated due to the breakdown of the glue holding the wire in place. Although hard to see, the wire is completely loose. In this example the sheet of fabric has separated. This style of duct was only produced for a few years.

Third generation duct. Interlock duct, available from the mid 1980's, and still produced. Uses a plastic extruded rib to maintain duct core structure, with glass wool and clear polyethylene sleeve. This example uses a nylon wire to clamp the fabric into the rib. This example has a perforated core, although most interlock duct is not perforated.

Core uses a fabric that has been ultra-sonically welded with steel wire. Uses polyester fibre and polyethylene sleeve. The core has better acoustic properties.

Figure 14 Field study duct examples

A section of glass wool from "Sidewinder" duct. The blackening is cause by dust passing out of holes or tears in the sleeve via the fibre. This example had many small holes resulting in a multitude of black regions.

A plastic branch take-off with tape still intact on the duct. This example is around 10 years old and shows that the taped joins have remained intact and secure.

Glued wire duct with polyester fibre and aluminised sleeve. An example of the duct used as a replacement for the field study. This example is R1.0.

Glued wire duct with glass wool and aluminised sleeve. An example of the duct used as a replacement for the field study. This example is R1.5.

Figure 15 Field study duct examples

An example of 10 year old duct with severely degraded polyethylene sleeve, exposing the bulk insulation. Sleeve should have stabilisers to improve longevity, but their removal reduces the cost of the sleeve. This system wasn't one of the ten field study homes, but was inspected during the study.

AS/NZS 4254 requires duct to be hung at regular intervals, but the standard has been ignored in this installation. Some of the duct is lying on the ground. This was from the same home as the photo on the left.

Figure 16 Field study duct examples

	Pre-retrofit						Post-retrofit							
	Estimated furnace efficiency (%)	System age (years)	Thermal efficiency (%)	Leakage efficiency (%)	System efficiency (%)	Annual gas usage (GJ)	Retrofit duct (m^2.K/W)	Thermal efficiency (%)	Leakage efficiency (%)	System efficiency (%)	Estimated annual gas usage (GJ)	System improvement (%)	Average gas reduction (GJ)	Estimated average annual greenhouse reduction (tonne CO2-e)
1	80	9	75	94	55	49	1.2	89	98	70	39	21	10	0.64
2	70	33	88	75	45	58	1.5	92	85	55	47	19	11	0.72
3	75	10	82	92	56	58	1.5	93	96	67	48	17	10	0.63
4	70	30	74	68	30	53	1.0	89	89	55	29	46	24	1.54
5	70	33	88	84	50	49	1.5	98	91	62	39	20	10	0.62
6	90	25	81	62	42	33	1.5	89	87	68	20	38	13	0.80
7	80	9	88	93	69	44	1.5	95	94	76	40	10	4	0.28
8	70	33	90	62	37	35	1.5	92	89	50	26	26	9	0.59
9	70	23	86	67	40	47	1.0	91	86	60	32	32	15	0.97
10	75	15	79	91	55	29	1.2	89	93	61	26	10	3	0.19

Table 13 Summary of results of system efficiency for field study

Home	Age (years)	Capital cost ($)	Amortised capital cost over 15 years at 7% discount rate ($)	Estimated annual reduction in energy consumption (GJ)	Estimated annual reduction in greenhouse emissions (tonne CO_2-e)	Emission abatement cost at 1 cent/MJ ($/tonne CO_2-e)	Emission abatement cost at 1.5 cents/MJ ($/tonne CO_2-e)
1	9	1400	154	10.1	0.64	83	4
2	33	2000	220	11.3	0.72	150	71
3	10	1298	138	9.8	0.63	63	(16)
4	30	1268	138	24.3	1.54	(68)	(147)
5	33	1378	165	9.7	0.62	83	5
6	25	1640	176	12.6	0.80	62	(17)
7	9	1400	154	4.4	0.28	397	318
8	33	1379	149	9.2	0.59	95	17
9	23	1808	198	15.3	0.97	47	(32)
10	15	1200	132	2.9	0.19	551	473

Table 14 Summary of abatement costs for field study homes. Assume amortisation over 15 years, 7% discount rate, emission intensity 63.6 kg CO_2-e/GJ. Cost in brackets (red) indicate negative cost.

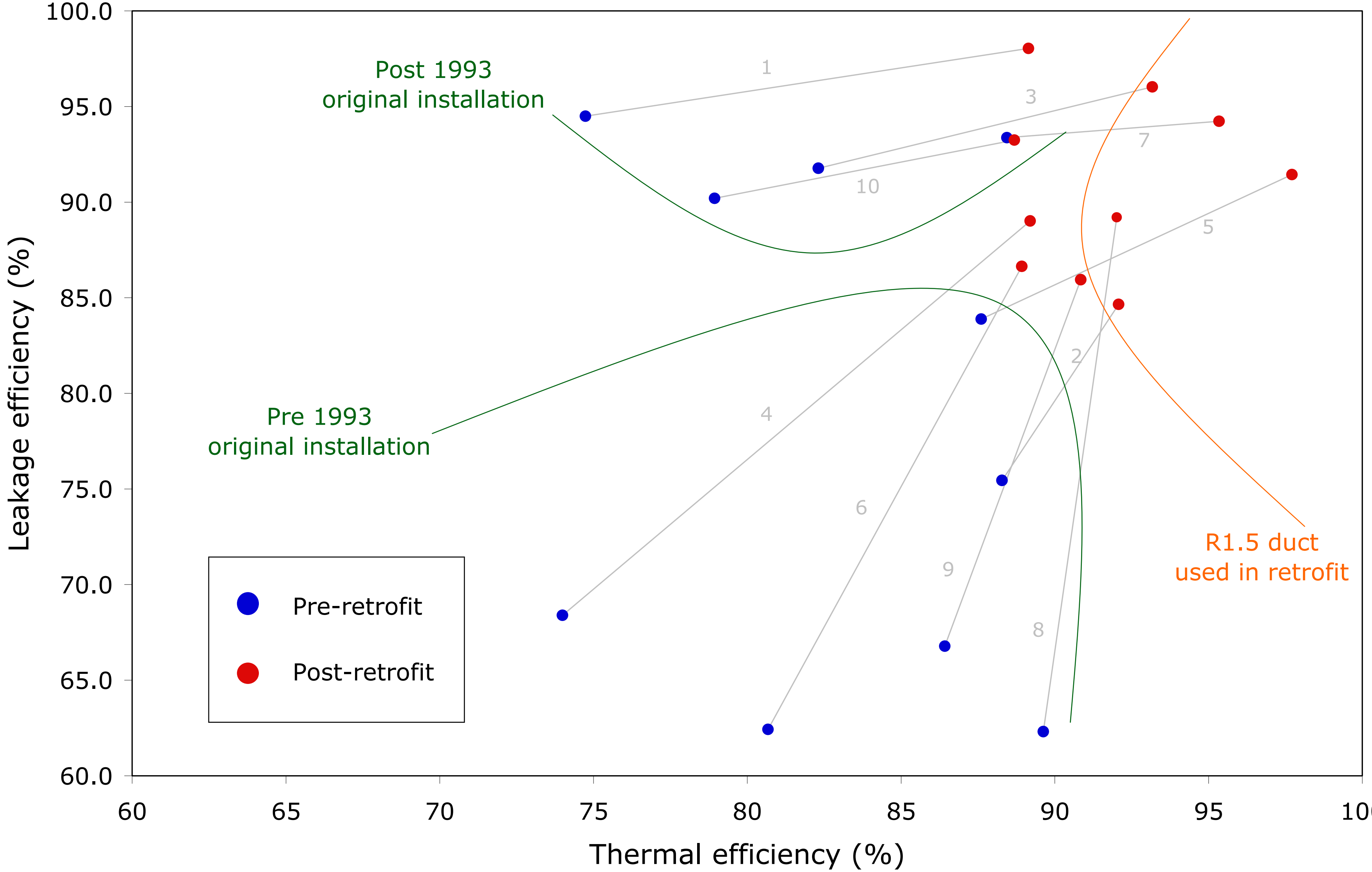


Figure 17 Leakage and thermal efficiency for the 10 field study homes, with pre-retrofit and post-retrofit results.

Figure 16 shows the leakage and thermal efficiency for all field study homes, for both pre and post retrofit. Although the sample size is small, a number of observations are apparent, which is consistent with the observations.

1. The post-retrofit results are clustered towards the high end of both thermal and leakage efficiencies, which is consistent with having new ductwork installed.
2. The older systems had higher leakage results, which is consistent with the type of duct used, and the deterioration of the older duct.
3. There is no correlation between thermal performance and age of the pre-retrofit data. Older systems used similar levels of insulation to newer systems.
4. The use of R1.5 duct in post-retrofit systems resulted in a better thermal efficiency.

Home	Building construction type	Approximate house area (m^2)	Average annual energy used for space heating (GJ)	Annual space heating energy/area (MJ/m^2)	Annual space heating greenhouse intensity (kg CO_2-e/m^2)
1	Brick veneer	152	49	322	20.5
2	Brick veneer	147	58	395	25.1
3	Concrete	80	58	725	46.1
4	Brick veneer	116	53	467	29.7
5	Concrete	80	49	613	39.0
6	Brick veneer	132	33	250	15.9
7	Concrete	112	44	393	24.9
8	Concrete	74	35	473	30.1
9	Concrete & weatherboard	145	47	324	20.7
10	Concrete & weatherboard	97	29	299	18.8

Table 15 Comparison of energy used, building construction type and home size before duct system retrofit

5.5 Observations

5.5.1 Leakage

The homes with newer systems showed significantly less leakage than the older systems. There was a clear correlation between the age of the system and the duct system leakage, where older systems show greater leakage. Systems that were greater than 25 years old showed leakage figures of greater than twenty percent, compared to five to ten percent for systems that were around 10 years old. All homes that used semi-rigid aluminium duct (Vulcan “Sidewinder” style) exhibited a large leakage measurement.

Three factors have been identified that may contribute the increased leakage over time. The first is the use of perforated (or acoustic) duct, which was used extensively until the 1980’s. The perforated duct has small holes punched into the inner core to reduce airflow noise. In theory, if the outer sleeve maintains integrity, the duct will maintain air tightness, however any small cuts or holes in the sleeve will render the duct non-air tight and contribute to air leakage losses. Interestingly, the older sleeve appeared to be in generally good condition for most of the sleeve area, in part because of the use of good quality, thick polyethylene. However there was evidence of numerous small tears and holes which may have been caused during the original installation by dragging the duct over building rubble under the house, and also due to the normal degradation of polyethylene.

The second factor was the degradation of the PVC tape used in the joins, which is discussed further in the following section.

Thirdly, older systems used sheet metal plenums and branches, which are not as airtight as the plastic branch take-offs introduced during the late 1980’s. The use of plastic fittings is discussed in section 2.1 and 7.

It was not possible to differentiate the relative contributions of the breakdown of sleeve in perforated duct, the breakdown of the joins caused by degradation of PVC tape, and the use of metal versus plastic fittings, with each factor confounding the correlation between age and the leakage of the system.

5.5.2 Taped joins

The tape appeared to be consistent for all systems, and used the Nitto (or equivalent) grey PVC duct tape. The taped joins appeared to be intact where sufficient tape had been applied. In the case of the older systems (> 25 years), the tape had lost its tack, and was able to be easily pulled off, although the tape appeared intact if left undisturbed. There were three systems in the study that were ten to fifteen years old, and the duct tape in all of these systems appeared to be in good condition, and maintained very good tack. It wasn't possible to ascertain whether the loss of tack in the older systems was due to natural deterioration of the tape, or whether the older tape was of inferior quality compared to the newer tape.

Some of the taped joins had generally tended to lift over a length of 20 to 100 mm, with the rest of the join remaining intact. The field study demonstrated the importance of winding of least three turns tightly around the join, and trying to cleanly apply the final end of the tape securely with a clean cut and avoiding tension at the end. Observations of joins that had insufficient tape applied showed a tendency to lifting of the tape, sometimes with a failure of the taped join. In some cases, there was sufficient tape around the sleeve of the duct, but insufficient tape around the collar surface of the fitting, which resulted in the duct pulling away or failing to effectively seal, even though the tape around the duct sleeve was largely intact. This demonstrated that it is important to place sufficient tape around the collar of the fitting, as well as the sleeve of the duct. It is common practice to pull the duct core onto the fitting, applying tape securely, then pulling the insulation, followed by the sleeve over the assembly, then finishing with at least three complete turns of tape, ensuring that sufficient tape is applied to the fitting collar to ensure that the joint does not pull away. A correctly fitted and taped join provides two layers of air tightness if non-acoustic duct is used.

The field study demonstrated that the PVC taped join is effective in ducted systems, but may be expected to deteriorate over time. The tape would be expected to maintain tack and strength for at least fifteen years, but will be expected to have lost most or all of its tack by thirty years. The study did not examine the possible improvements in PVC tape that may have occurred over time that may have improved the longevity of tape. Although the use of draw bands or cable ties is rare in residential systems, the use of mechanical fastening, in addition to tape, would be expected to increase the longevity of the join. However further research would be required to ascertain the optimum long term duct-to-fitting sealing method.

5.5.3 Degradation of sleeve

The outer sleeve of flexible duct is generally composed of one of two materials. The first is polyethylene, which is extruded continuously as a cylindrical shape. Polyethylene sleeve is usually purchased by duct manufacturers, and is usually printed with various markings. The second method to produce sleeve is by using metallised PET films. Metallised sleeve has been produced since the 1990's.

All the homes used an outer sleeve composed of polyethylene. The older sleeve was generally approximately 120um, which is in contrast to 75um being more commonly used now. There was a large range of degradation of the sleeve, with some being in excellent condition, while other sleeve showed significant deterioration, even within one system. Polyethylene can be broken down by a range of environmental influences including ultra-violet radiation, heat and oxygen. It is commonly assumed that the main influence on polyethylene is ultra-violet degradation, however it is not obvious that this was always the main cause of sleeve deterioration. In instances where the sleeve has light impinging upon it, the sleeve is more likely to have broken down, but breakdown also occurs in very dark areas under homes. In these cases, heat may have been a contributor, or there have been other environmental or manufacturing contributors.

5.5.4 Return air grille sizing.

Most of the households tested used under-seized return air grilles. Heating appliance manufacturers specify the recommended open area for return air grilles, and provide specifications for both filtered and non-filtered configurations. The use of an under sized return air grille increases the static pressure drop across the grille, thereby decreasing the flow rate through the system. This leads to an increase in temperature difference across the furnace, which results in an increased temperature through the supply ductwork. The total energy delivered by the appliance is not substantially affected, but the temperature of the delivered air through the ductwork is raised, which leads to increased thermal energy losses due to a greater temperature difference between the duct airflow and ambient. The reduction in flow rate may also affect the performance of the system through a reduction in effectiveness of air mixing from the supply register and grilles.

Competitive pressures in the heating market encourage the use of under sized return air grilles, and it is common practice to under-size the return grille. There may be a number of reasons for under-sizing. Experienced installers regularly use rule-of-thumb calculations, which may be based on empirical experience gained over a number of years. Without testing, it is not obvious that a system is under performing due to the use of an under-sized return air grille. Appliance manufacturers publish installation manuals, which provide recommended return air sizes, however installers are often unaware of these specifications, or otherwise ignore them. Very tight margins often necessitate the use of minimum specification products in order to remain competitive.

A number of field study homes were supplied with return air grille filters in instances where no filter was installed.

5.5.5 Cyclic losses

Gas furnaces usually have a limited operating range in terms of power delivered, and older units provide only one power level. The system controls the living space temperature via the thermostat by cycling on and off. Depending on the furnace, the system fan will run for a period after the burner has stopped.

In addition to the leakage and steady state thermal losses, the system will lose some of the energy that is absorbed by the thermal mass of the system components that is not collected during the fan run-on period. It was beyond the scope of the field study to measure the cyclic losses, however ANSI/ASHRAE Standard 152-2004 (ASHRAE 2004) provides an allowance of two percent cyclic losses.

5.5.6 Zoning

The use of motorised dampers allows the home to be separated into heating zones. Typically, the living areas and bedroom areas will be separated, however, many configurations are possible. In theory, the only restriction on the use of zones is the capacity of the furnace to operate with reduced airflow. None of the homes in the field study used motorised dampers to zone areas.

5.5.7 Furnace efficiency

The gas input of the furnace was measured by observation of the mains gas meter while the furnace was running. The meter was observed for around one minute, and allowed the minor dial on the meter to rotate four times. This provided an energy input, but the energy output required measurement of the airflow output from the furnace. This requires measurement of the axial air velocity through the duct, and the temperature. Taking known constants, the power delivered can be calculated.

A number of attempts were made to measure the velocity and temperature, however there was found to be significant variation in the readings across the cross section of the duct. This seemed to be particularly the case at a point close to the output of the furnace, which is where the measurements must be taken. The air velocity across the duct varied from 1.0 to 10.0 metres per second, with temperature variations of typically 4 ^{o}C. Although the air velocity can be measured in an axial direction, the turbulence contributes to inaccuracies in determining the aggregate airflow. In theory, the variation across the duct can be handled by measuring at a large number of points (say, 30), and averaging over the points. This is possible in a laboratory environment with the end of the duct open, but very difficult with the duct in-situ because measurement must be taken through the wall of the duct while the system is running. The accuracy is constrained by the accuracy of the air velocity measurement, the temperature measurement and the error arising from the averaging process with the use of discrete points. It was deemed unsatisfactory to use direct measurement due to the inability to obtain results with sufficient accuracy.

Given this, the efficiency of the furnaces was obtained directly by the use of manufacturer data where possible, reading the label on the furnace, or estimates based on the age of the equipment. This figure was used to derive the power output of the furnace based on the measured gas input. In practice, small errors in the estimation of furnace efficiency do not affect the duct efficiency results, although they will affect the overall system results. The given efficiency figures led to calculated data that was in accord with the expected results.

5.5.8 Furnace economy mode

Some furnaces have an economy operating mode, which allows the furnace to operate at half input power (gas usage) and half airflow. In theory, the furnaces would be expected to operate for approximately twice as long to achieve the same heating supply into the living space. According to Andrews (2003), the increased residence time of the air in the duct will increase thermal losses due to ductwork. The increase in thermal losses can be obtained from a straightforward theoretical calculation. For example, assuming that 15 percent of the input heat is lost via conduction under full-capacity operation, then for a modulating furnace operating under half capacity mode, the heat loss would approximate 28 percent from the following equation:

$$\begin{aligned}\text{Heat loss} &= (1 - (1 - 0.15)^2) \\ &= 0.28\end{aligned} \qquad (9)$$

Andrews (2003) confirmed the theoretical results with experimental data, concluding that heat input and airflow rates can seriously detract from the ability of the duct system to deliver heat efficiently into the living space.

The results also suggest that heat losses will be minimised through the use of as small ductwork as the design parameters will allow. The choice of size for each section of ductwork is determined by a trade-off between air velocity and static pressure drop through the ductwork. The heat loss through duct walls is largely independent of flow rate within the range of flow rates encountered in practice, which implies that increasing the flow rate through a section of duct will result in a smaller proportion of the energy being lost. It also suggests that a system containing less ductwork will operate at reduced heat loss.

5.5.9 Under-floor space

All of the homes used under-floor ductwork, although many current homes use in-ceiling ductwork as a consequence of building on a concrete slab. One home was considered for the field study, but was rejected because of insufficient space below the flooring. There appeared to be no under-floor access point, and the ground level was slightly lower under the home relative to around the perimeter. The home in question had chipboard flooring, with mostly carpet, and some tiling. It may have been possible to lift some of the carpet at strategic points, and cut and remove sections of flooring to gain some under-floor access, but building work of this nature was beyond the scope of the project. In theory, with planning, the project would not be difficult once the decision was undertaken to gain under-floor access. The main impediments are the additional costs, and that work of this nature is usually beyond the scope of heating contractors, who would consider the job "too hard".

There has been a trend by builders towards using fewer courses of brickwork as a cost saving measure over time. The ductwork is installed before the flooring is laid, but after the bearers and joists are fitted. The access problem is likely to be repeated many times over the coming years.

5.5.9 Thermal rating of pre-retrofit ductwork

Most of the pre-retrofit ductwork used glass wool insulation, measuring 13 to 17 mm thickness, which would approximate to R0.4. There are currently two glass wool manufacturers supplying product to the Victorian market, CSR Bradford and Fletchers. Current glass wool has a declared value of R1.0 for 45 mm thickness, and R1.5 for 63 mm thickness.

There was a small amount of polyester fibre used in the newer installations, which weighed from 220 to 280 grams/m^2, which is consistent with R0.6 duct.

5.5.10 Dust build up

At least two of the homes had used a duct cleaning service to clean the ductwork. In both cases, tears were visible on the inner core, which suggested that there had been some protrusion from the inside of the duct. In one case, the performance of the ducted system had deteriorated to the point where the householder elected to use alternative forms of heating. It was not possible to confirm that the tears were caused by the duct cleaning operation, however it seemed reasonable to implicate the duct cleaning procedure. The study did not attempt to address the benefits or otherwise of duct cleaning, however the accidental tearing of ductwork is detrimental to the efficiency and performance of ducting systems. The use of a filtered return air grille will reduce duct build up within the ductwork and fan. Although rarely performed, the maintenance of furnaces is recommended, including the cleaning of the fan, which can suffer from significant dust build-up, and may contribute to a fire hazard. According to The Melbourne Metropolitan Fire Brigade (2002), there is no evidence that dust build-up in ducts has caused a fire.

5.5.11 Client feedback

All of the clients commented that their heating system was performing better than it did previously. Some of the clients commented that the heater brought the temperature up to the thermostat set point much faster than it had previously. These were mostly homes with high leakage. The same clients also commented that the airflow from the registers was much higher than it had been previously. Interestingly, the velocity at the registers improved, even where there wasn't high leakage in the pre-retrofit systems. The reason for this wasn't clear, but may have been because of an improved quality of installation resulting in straighter duct with less bunching and bending. The air velocity measurements confirmed that the airflow was much higher in the systems that had high pre-retrofit leakage. The velocity measurements suggested that the pre-retrofit leakage estimates may have been understated.

Some effort was made to design the ductwork layout to balance the heat flow to all areas of the home, and a number of clients commented that rooms that had previously been cool were noticeably warmer than they had been previously, relative to the rest of the home. Only one home required floor boot adjustment to provide balancing. The floor boots have a butterfly damper installed to allow each room to be adjusted for airflow, allowing balancing.

5.5.12 Uncertainties

There is a range of uncertainty associated with the measurement procedure for both the thermal test and the leakage test.

The pressure test provides an air volume due to leakage at a specified pressure. The homes with very high pre-retrofit leakage rates were difficult to pressurise, and the proportion of leakage in the operating system could not be directly measured. Based on the air velocity measurements, the leakage results for the worst performing homes was probably under-stated. The air leakage results would likely become more accurate as the leakage decreases. For example, one home measured a very low post retrofit leakage, which correlated with a leakage loss of 2 percent. The result is likely to be a good approximation, in absolute terms, to the actual figure. The worst performing home resulted in a leakage of an estimated 45 percent. While this result may have been a good result in proportional terms, the tolerance was greater in absolute terms.

The temperature measurements were conducted with a calibrated thermometer, with the same thermometer being used throughout the study. The calibrated accuracy of the thermometer is stated as 0.5 ^{o}C, with the measurement consistency better. The measurement of the airflow at the supply registers appeared to be reliable and consistent. The measurement of the airflow in the main supply duct was subject to greater variation, and the temperature varied across the cross-section of the duct. This was dealt with by averaging the result across the duct as best as possible. Given that the temperature probe was 100 mm long, and required insertion into the duct, it was not possible to perform an averaging process precisely.

The main barrier to the consistency of the temperature measurement was the issue that each register was measured at a slightly different time. The overall measurement relied on the registers being supplied air at a constant temperature from the furnace. This problem was dealt with in two ways. Firstly, the furnace was allowed to run for at least 15 minutes to allow the system to reach steady state. The thermal mass of the furnace and ductwork results in a negative exponential rate of change until the temperature reaches steady state. The second issue is that the home heats up while the furnace is running. This was dealt with by opening a number of doors and windows while the system to running to maintain a steady temperature inside the home.

5.5.13 Static pressure

The static pressure was taken at various points within some systems, including the outlet registers, return air grille and furnace. While the pressure readings provided some indication of the operation of the system, they did not provide a measure of the direct energy efficiency of the system, and are not included in the report.

However, there were two measurements of interest. Firstly, the pressure drop across dirty filters in return grilles was substantial when the filters were not cleaned. In one instance, the client reported that the filter had not been cleaned for many years, and the filter was the original unit, which was 33 years old. The pressure drop across the filter measured 45 Pa, which significantly reduced the airflow through the system. Secondly, the use of "top hats" over the return air duct was found to increase system resistance by approximately 20 Pa.

A number of client commented that they were not given advice or instructions on how to clean the filters in return air grilles. Return air grilles are discussed further in section 5.5.4.

6. Thermal test rig

Broadly, there are two methods to dynamically measure the thermal resistance of flexible duct. The first method is to connect a fan and heater to a length of straight duct, leaving the end open. By measuring the airflow, and entry and exit temperatures, the thermal resistance can be determined. The main drawback with this design is that the temperature must be measured to a high degree of accuracy in order to obtain accurate results, as there will typically be a small temperature difference. From Levinson et al. (2000), the thermal resistance can be determined by:

$$R = \frac{4l}{\rho c_p u d_{hi} \ln\left(1 - \frac{\Delta T_{12}}{\Delta T_{1a}}\right)} \qquad (10)$$

where
R is the thermal resistance (m^2.K/W)
l is the length of duct under measurement (m)
ρ is density of air (1.2 kg/m^3)
C_p is specific heat capacity of air (kJ/kg.K)
u is velocity through duct (m/s)
d_{hi} is convection coefficient, and is given by
$d_{hi} = 4$ Ai / Pi
where Ai is the duct inner cross sectional area (m^2)
P_i is the circumference of the inner duct (m)
ΔT_{12} = temperature drop across the duct length (^oC)
ΔT_{1a} = temperature elevation of the duct air temperature at the start of the run over that of the ambient temperature (^oC)

Figure 18 Method 1 for testing thermal resistance of duct. A straight length of duct is connected to a fan and heater assembly, with measurement of temperature at the open end, and just after the heater.

The second method requires feeding the open end of the duct back into the heater/fan assembly to reheat the air. Measurement of the thermal resistance is determined by the heating power required to maintain a constant temperature within the duct assembly. The test rig was based on a method proposed by Cox-Smith (2006). Following the construction of the rig, it was discovered that similar testing had been conducted by Fricker (1997) for clients some 10 years earlier, with a slightly different design and Fricker and Johnstone (2007) had developed a model for the prediction of thermal resistance based on a number of parameters. Yarbrough (1991) had used a similar design in 1991 to measure the thermal resistance of rectangular sheet metal duct with various configurations of insulation.

This method is sometimes referred to as the “donut test”. With the financial support of Sustainability Victoria, a thermal test rig was constructed and operated.

6.1 Apparatus

Omron E5AK-AA2 PID process controller
Omron E53-V34 voltage amplifier
Omron TC24CF & TC11PIND industrial air sensor
Stokes 4061-U heating elements
Fantech APB-0314AA5/24 belt drive fan
Baldor BL-KBWT-210 PWM DC amplifier
Baldor BL-KBSI-240D signal isolator
Digital voltage meters to measure heater voltage and current
Thermally insulated enclosure

Figure 19 Close-up view of thermal test rig heater/fan assembly. Display unit at centre/left is heater PID controller. To the right are displays showing DC voltage and current of heater.

6.2 Method

Two lengths of duct, each 6 metres long, are connected to the test rig, with a joiner between the two lengths. The joiner contains the thermocouple that provides the temperature feedback for the PID (proportional, integral, differential) controller. The PID controller provides a proportional voltage output for input into a DC amplifier, which drives the heating elements. The proportional output is in contrast to the more common method of heater control which uses a binary on/off output, which is pulse-width modulated, usually with a cycle time of several seconds up to several minutes. The benefit of the proportional output is that once the system has reached steady state, the DC voltage and current outputs can be read directly.

The controller is set with a “set value” temperature, which the controller attempts to match with the “actual value”. The PID controller attempts to match the set value with the actual value as quickly as possible. Although the PID is programmable to provide for a range of response curves, the default values were retained.

After connecting the duct, the fan is set to a preset position, and the controller set to the required temperature. During operation, the air inside the assembly slowly rises, and eventually reaches the "set value". Ideally, the controller will reach the temperature quickly without overshoot. In practice, it takes around 30 minutes for the temperature to stabilise within the assembly. Once the system has reached steady state, the heater voltage and the current are read directly, together with other parameters, and fed into the following equation to arrive at the thermal resistance.

$$R = \frac{(L\Pi d)(T_{in} - T_{out})}{(V_{heater} \times I_{heater}) + P_{fan}} \qquad (11)$$

where
R = thermal resistance (m^2.K/W)
L = total length of duct (m)
d = diameter of duct core (m)
T_{in} = temperature inside the duct (^oC)
T_{out} = ambient temperature (^oC)
V_{heater} = DC voltage across the heating element (volts)
I_{heater} = DC current through the heating element (amps)
P_{fan} = absorbed power from fan (watts)

One of the drawbacks of the rig as constructed is that the fan motor is mounted outside the airflow, and connected to the fan via a belt. The power contribution between the power loss from the motor, and the fan absorbed power, is separated. With hindsight, it would have been better to place the fan motor within the measured airflow as it is easier to directly measure the fan electrical power, which consists of both the motor and electrical losses, and fan absorbed power. The impact of the fan absorbed energy becomes apparent when the heater is turned off, and the duct being measured has a high R-Value – the system still warms despite the heater not contributing any energy. In order to determine the fan absorbed power, the rig was run at a number of temperatures with duct connected, then the absorbed power was determined iteratively by including the absorbed power into equation 12 to arrive at a consistent R value across a range of temperatures. This was easily accomplished, and was found to be approximately 190 watts at a fan controller output of 50 hertz. The rig was consistently run at the same fan speed for consistency across different sizes and temperatures.

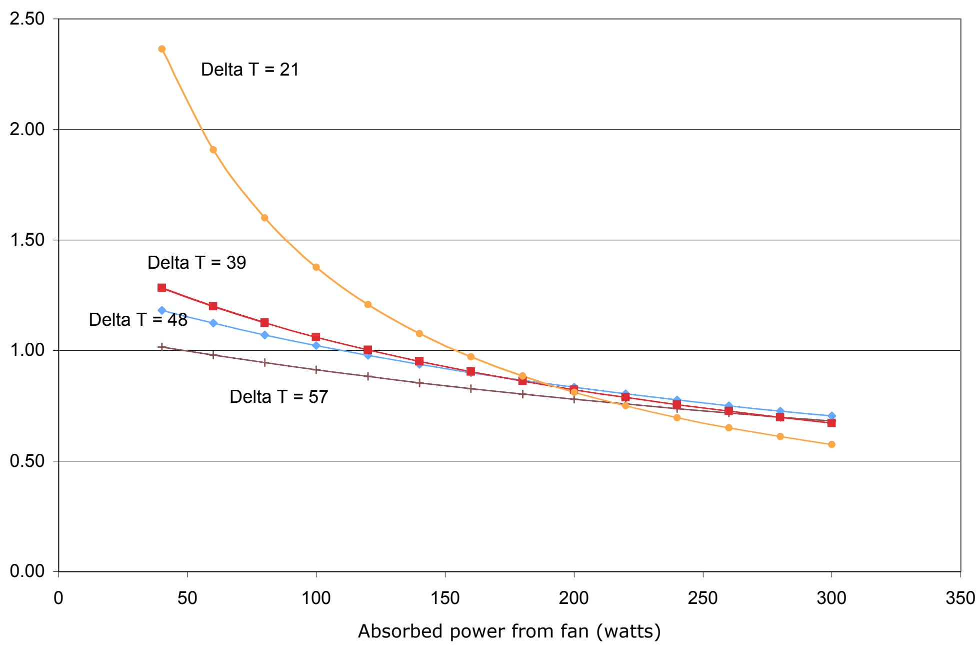


Figure 20 Calibration of thermal test rig to account for heat due to fan absorbed power.

Figure 21 Thermal test rig with 2 lengths of 6 metre flexible duct connected in a "donut" configuration. Heater/fan assembly is the box at the centre.

The thermal losses of the rig itself needed to be estimated. The fan/heater cabinet was fully encased with glass wool batts, and the inside cylinder housing the fan and heater was lined with reflective foam insulation. The cylinder was 310 mm diameter with a length of 800 mm, providing an area of 0.78 m^2. This can be compared to the area of duct under test of typically 6 to 12 m^2, constituting 6 to 13 percent of the test area. The R-Value of the fan/heater cylinder was assumed to be R3.0. Given that the duct under measurement was typically R0.2 to R1.7, the difference between the estimated and actual thermal resistance was minimal, and contributed marginally to the measurement uncertainty. In order to use the apparatus to provide a certifiable test report, it would be necessary to measure the actual thermal resistance of the rig.

The length of the duct was measured along the longitudinal centreline of the duct. Ensuring that the duct was fully stretched was slightly problematic, as it required the installation of stoppers to prevent the duct from pulling towards the centre of the donut. The tendency to pull inwards has the effect of shortening the overall length of the duct and increasing the thickness of the bulk insulation, thereby improving the thermal resistance. In practice, two 6-metre lengths of duct were connected in series was found to measure around 10.5 metres length when connected in the donut configuration. This was due to the outer radius of the donut constraining the overall length, with the inner radius of the donut retaining flexibility. The measured length was used in equation 12, but the choice of measured length could be a point of debate in relation to the stated thermal resistance of the product.

The PID controller used a thermocouple that was positioned at the mid-way point, at the join between the two lengths of duct. This was chosen as a representative point having a temperature that is approximately mid-way between the entry and exit of the test rig.

Table 18 provides a summary of some of the test results. A number of duct configurations were tested, including nude core, insulated duct with both polyester fibre and glass wool.

6.3 Results

Sample description	Diameter (mm)	Length (metres)	Duct temperature (°C)	Ambient temperature (°C)	Delta T (°C)	Heater power (watts)	Fan absorbed power (watts)	Rig power loss (watts)	Duct power (watts)	Calculated R-Value (m^2.K/W)
Silver sleeve duct with R1.5 glass wool	250	10.5	100	23.8	76.2	231	190	20	401	1.71
Silver sleeve duct with 220 gsm polyester fibre	250	10.5	80	23.0	57.0	557	190	15	732	0.67
Silver sleeve duct with R0.85 polyester fibre	250	10.5	60	21.0	39.0	120	190	10	310	1.09
Nude core, glued duct, clear film inside, metallised outside	250	10.5	60	21.0	39.0	1495	190	10	1675	0.20

Table 16 Thermal test rig results.

6.5 Conclusions

The thermal test rig performed as expected, and provided consistent test results. The use of a thermal rating of R0.15 m^2.K/W as a good approximation for the external air film of duct, by the Australian Building Codes Board for the Building Code of Australia, has been validated.

Three drawbacks of the rig were identified. The first related to the design using the fan motor external to the airflow, which required calibration, and which introduced a small amount of uncertainty into the test results.

The second problem was that the flexible duct required bending to form into a donut configuration. This resulted in the length of the duct along the centre-line being less than the usual straight length. The duct had a tendency to take the minimum length by pulling in to the centre of the donut, and the use of holders or brackets to constrain the duct will reduce the effectiveness of the bulk insulation within the duct. The results are dependant on the measurement of the actual length, and the tendency to reduce the overall length will tend to improve the thermal resistance due to the fibre being compressed slightly to a shorter length. In practice, a certified test would require measurement accuracy to better than 10%, and therefore the length would become an important consideration. A better configuration would require that the duct under test be formed as a straight line to ensure that the measured length is accurately established. This would require the installation of an insulated fitting to form a 180-degree turn to feed the airflow back through the assembly.

The third issue related to the length of time required to reach steady state, being around 30 minutes. For the purposes of the project, the time taken to reach steady state was not important, however in a professional laboratory that charges hourly rates, the length of time becomes an important consideration in the financial viability of duct testing. The test only directly measures the steady state thermal losses, and does not account for cyclic losses through the absorption of heat by the thermal mass of the system. Further studies would need to be undertaken to ascertain the additional energy losses, and how much of the energy absorbed due to thermal mass is recaptured during the fan run-on period. In a ducted heating system, the energy consumed in heating the thermal mass of the ductwork can be lost if the fan does not run for a sufficient period. ANSI/ASHRAE Standard 152-2004 defines the lost energy as the cyclic loss, and allows a loss of two percent for flexible duct.

7. Pressure test rig

Victorian ducted heating systems use plastic branch-take-offs (BTO's) with flexible duct for air distribution, and plastic grilles or registers for supply outlets. A test rig was constructed to measure the leakage from this type of air distribution system. It is commonly assumed that a duct joint that is sealed with PVC tape provides an effective airtight seal. The use of sealants and draw bands is recommended in section 2.8.4, part (d) of AS/NZS 4254-2000, but in practice, their use is almost unheard of in the industry for residential systems. The industry uses almost exclusively Nitto brand or similar PVC tape to secure flexible duct to the collars of BTO's, starting collars and joiners. Other methods of securing duct have been used in Australia, such as Venture Tape 1669B, or proposed methods, such as Donnelly (2003b), which aims to eliminate tape and draw bands completely. There is some debate within the industry as to the effectiveness and longevity of PVC duct tape, which has also been addressed in section 5.5. There is also a potential problem arising from the use of cheaper imitation PVC tapes, which are imported at lower cost than Nitto brand tape. An aerosol-based duct sealing technology has been developed at the Lawrence Berkeley Laboratory in California by Mark Modera, and was bought by Carrier in 2001 (Lawrence Berkeley National Laboratory 2008). The sealing technology uses small adhesive particles in aerosol form, to deposit into gaps in ductwork, thereby reducing air leakage.

A significant amount of research has been conducted in North America on the effectiveness of duct tapes (for example Sherman and Walker 1998). It can be confusing comparing North American studies to the Australian context for two reasons. Firstly there is differing terminology in relation to tape. For example, the "duct tape" commonly referred to in the United States is closer to the Australian "gaffer" tape, and there are often differing views on tape within each country. There appear to be many types of seals in use in North America for HVAC systems, including "duct tape", "packing tape", "foil tape", "mastic" and "butyl tape", among others.

Secondly, the type of joint that is under test is not frequently encountered in Australian ducted heating systems. The Sherman and Walker (1998) study tested a "round, right angle, metal-to-metal joint typical of a duct to plenum connection". This type of connection is rarely used in residential ducted heating systems, other than the use of a similar joint at the connection to the furnace and return air box, which frequently use sheet metal "starting collars", which are screwed or riveted to the furnace sheet metal. All of the ductwork connections are made by pulling duct firmly over plastic branch take-offs, and securing with securely wrapped tape.

The aim of the test was to ascertain the amount of leakage from the PVC taped method and either validate or invalidate this sealing method. The purpose of the test wasn't to assess whether the sealing method is the best method as it was beyond the scope of this report, and further research would be required. In comparison, the Sherman and Walker study was more comprehensive, with the test run over two years, and included cycling with heated air to age the joins under test, with a number of tapes and seals under test.

7.1 Apparatus

Air compressor, 7 bar
Festo LRP-1/4-0.7 precision, pressure regulator
Festo SFE1-LF-F10-HQ6-P2U-M12 air flow meter
Energy Conservatory DG-700 pressure gauge
Two short lengths of 150 mm insulated flexible duct
One double branch-take-off
Air valve
Air tubing
Nitto PVC duct tape

7.2 Method

The test rig consisted of a double BTO, with two 200 mm pops, and two 150 mm pops. Two separate lengths of duct were connected forming a pair of sealed loops within the rig, thereby creating one sealed enclosure. Each of the ducts was standard core, with sleeve. The inner core was pulled firmly onto the collar of the BTO, and taped, followed by the outer sleeve. Uninsulated duct was used to enable a visual inspection of the system to determine whether any air leaked from the duct core to the inside of the duct sleeve. If there were air leakage within the core/sleeve cavity, the sleeve would be expected to expand slightly and balloon.

Two holes were drilled, and fittings attached, into the BTO in order to provide an external air supply, and a means to ascertain the pressure within the rig. An air compressor was connected to the BTO via a Festo low-pressure precision air regulator, valve and Festo precision air flow meter. Connections were sealed with 3 complete turns of Nitto PVC duct tape over the core of the duct, followed by another 3 turns over the sleeve. Internal pressure was measured using an Energy Conservatory DG-700 pressure gauge.

Figure 22 Set up of pressure test rig, showing BTO, duct, pressure regulator, flow meter, valve and manometer.

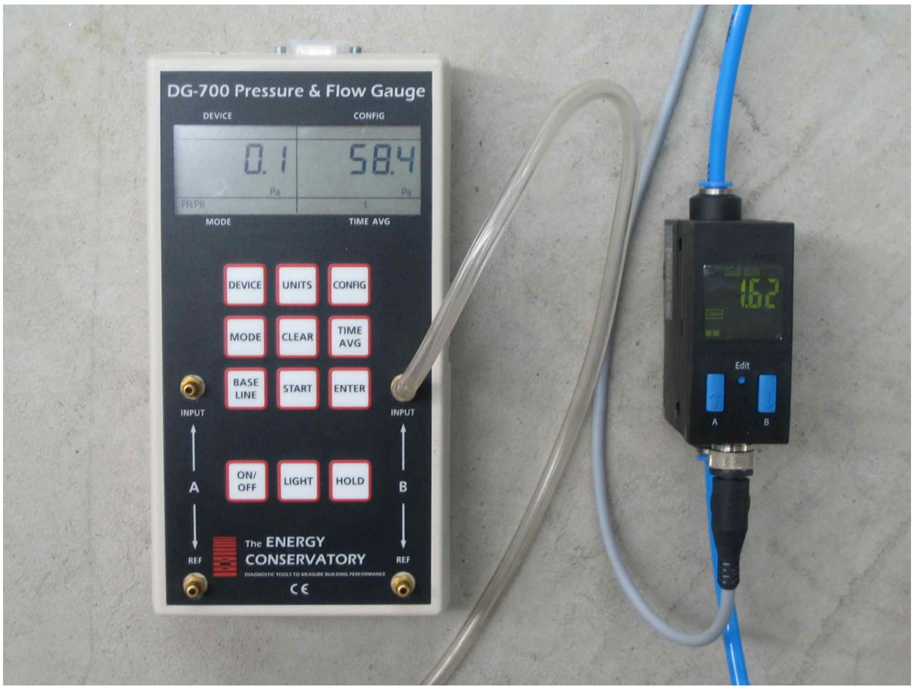


Figure 23 Close up of Festo flow meter and Energy Conservatory DG-700 pressure gauge

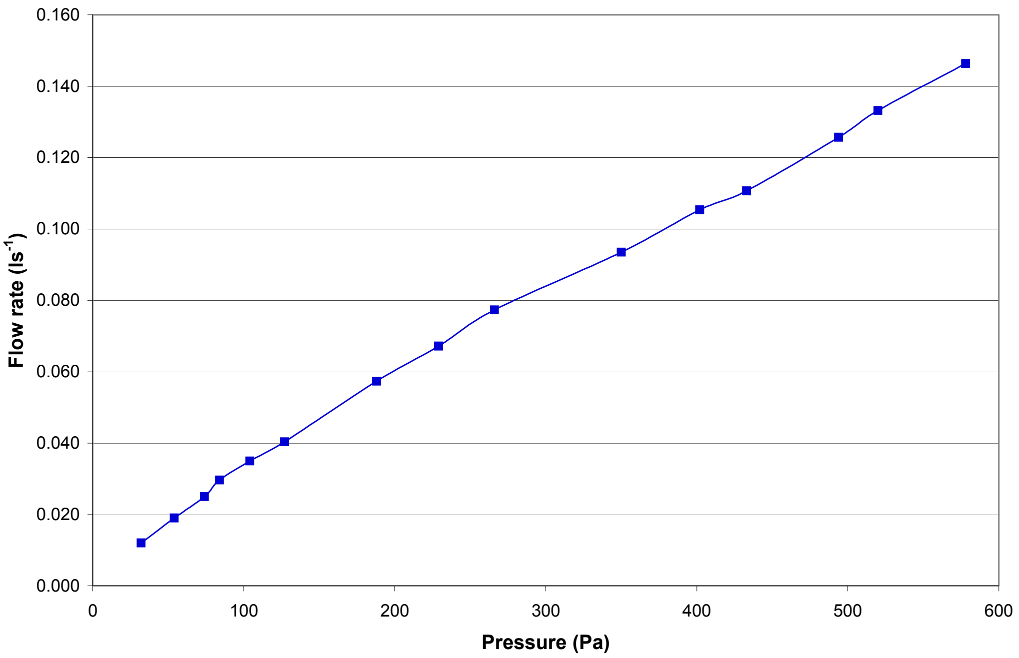


Figure 24 Pressure test results of sealed duct and BTO unit.

7.3 Results

The compressor was turned on, with the pressure set at around 7 bar. After setting up the apparatus, the valve was opened, allowing air to flow into the sealed assembly. The air regulator was adjusted to control the pressure of the incoming air. The low-pressure precision regulator was required because the inflation pressure (maximum of 600 Pa) was substantially below that of the supply pressure (7 bar or 700,000 Pa). The inflation of the assembly took a number of minutes as the duct expanded slightly to accommodate the additional pressure. A steady state was defined as a static pressure reading, combined with a static airflow reading. At this condition, the incoming airflow through the regulator matched the outgoing airflow, or leakage. The airflow was very low relative to the usual airflow through a ducted system, but was noticeable though an audible noise, which was accentuated through the use of 6 mm hose.

The pressure and airflow were measured at fifteen points. Each reading took a number of minutes to perform, as the apparatus was allowed to reach steady state. Figure 12 graphs the results of the test. Although the pressure in normal systems would not be expected to rise above 100 Pa, the test ran up to 600 Pa since flexible duct is usually rated up to at least 600 Pa. There is a clear linear relationship between pressure and airflow, which is consistent with the expected results.

7.4 Conclusions

In normal operation of gas ducted heating systems, it is not obvious that there is any leakage from ducted joins to BTO's. It was interesting to observe a small leakage in the system by way of the meter readings and audible noise of airflow within the air fittings, although there was no observable leakage from the joins themselves through audible noise or by touch. It seems that the air leakage must have been occurring along the seams of the joins. It was noted that the outer sleeve of the duct did not expand, further indicating that leakage was not occurring through the duct itself, but must have been at the joins. The PVC duct tape appeared to provide a good seal, but it could not be considered completely airtight.

A normal ducted heating system would be expected to operate at a static pressure of between 10 and 50 Pa. Taking a high pressure of 100 Pa the measured leakage was 0.035 litres per second. Assuming that each connection leaks by a similar amount, the average leakage per joint would be approximately 0.009 litres per second at 100 Pa. On average, an eight point ducted system will contain 25 to 30 joints, amounting to less than 1 litre per second system leakage attributable to leakage from duct to plastic fittings within the system. A typical gas ducted heating system will typically deliver 300 to 500 litres per second, which gives a leakage from duct to plastic fittings of less than 1 percent.

This result is interesting in comparison to US studies, which show dramatically more leakage in field studies, and provides consistent results with the household field study, where the replacement of the ductwork shows a leakage of less than five percent. The Sherman and Walker (1998) study shows dramatic differences between the sealing capabilities of different sealing techniques.

From an Australian perspective, the field study, and the pressure test rig validated the use of PVC tape combined with plastic fittings, provided that the join is completed correctly with good quality tape. The plastic fittings usually have partial beads on the collar, and typically allow more than 50 mm of duct to be pulled onto the collar, with more than 100 mm available to wrap tape around the collar to provide an adequate seal. The fittings provide a solid, clean and grease-free surface to allow good adhesion.

The remaining leakage is almost certainly due to sources other than duct-to-plastic fitting connections. Some of the residual leakage is probably due to some leakage around the starting collars on the furnace or return air box, and possibly the sheet metal edges on the furnace where the panels are screwed onto the furnace frame, particularly if the foam seals are not present or have deteriorated. The standard method of securing duct to furnaces is with the use of starting collars, which are usually sheet metal rings, with an array of foldable tabs around the perimeter. The collar is pushed into a round hole of the furnace, and the tabs are folded at ninety degrees inside the furnace housing, with some of the tabs being riveted or screwed. These are sometimes siliconed. This is typical of the type of join that has been researched in North America, and which contributes to leakage. In the Australian context, these collar-to-furnace join are usually left un-taped. While beyond the scope of this report, it would be relatively straightforward to manufacture an alternative fixing method that could provide a guaranteed low leakage join to the furnace.

It is noteworthy that the California Energy Commission (2005) has approved the use of a cloth-back duct tape with a special butyl adhesive manufactured by Tyco and sold as Polyken 558CA or Nashua 558CA. The tape passed Lawrence Berkeley Laboratory tests comparable to those that cloth-back rubber-adhesive duct tapes failed. In general, United States requirements mandate the use of duct closure systems that meet the applicable requirements of UL 181, UL 181A, UL 181B, or UL 723.

8. Alternatives to replacing ductwork

In addition to comparing the level of insulation that will result in the lowest lifetime cost or greenhouse emissions, a householder may elect to consider alternatives to upgrading the duct system. The discussion in section 4.2 considered the situation where a householder has already decided to install the ducted heating system, and the choice must be made as to the optimum level of duct insulation. Three options are considered to provide a context for ductwork replacement. A more detailed analysis of the greenhouse implications for a range of heating options is provided in George Wilkenfeld and Associates (2007).

Options available to a householder could include:

1. Carrying out a replacement of the ductwork, with a choice of insulation levels.
2. Replacing the ducted heating furnace only, with a choice of efficiency.
3. Installing or upgrading the ceiling, wall or floor insulation.

8.1 Household insulation

The performance improvement in terms of cost and greenhouse emissions will depend on the performance of the existing parameters in the home. For example, a home with some no ceiling insulation at all will benefit more than a home that already has some ceiling insulation. According to ABS (2005), virtually every Victorian home has some form of ceiling insulation, most of which is batts, followed by loose fill. The ABS statistics do not provide the thermal rating of the installed ceiling insulation. However less than half have wall insulation, of which most of which are likely to be newer homes.

Insulation location	%
Roof/ceiling	98.7
Walls	40.3
Floor	0.9
Other	0.4

Table 17 Where insulation is installed in homes in Victoria 2005. Source: ABS (2005)

Insulation type	%
Batts – fibreglass/wool/poly	62.8
Sisalation/reflective foil	2.5
Loose fill – cellulose fibre	7.2
Loose fill – rock wool	7.8
Loose fill – other/unknown	7.8
Foam/plastic	1.1
Polystyrene sheets	0.2
Insulated cladding	0.1
Other	0.6
Not known	12.5

Table 18 For homes that have ceiling insulation, the main type that is used. Source: ABS (2005)

For existing homes, the installation of ceiling insulation is a straightforward operation. The installation of polyester fibre or glass wool batts can be carried out professionally or the able householder. The insulation of walls is more difficult, but blown in Fibretex can be used for brick veneer construction, but is relatively expensive. Alternatively, Pears (2007b) retrofit batts into brick veneer walls by removing sections of plasterboard, then sliding batts into the cavity, and refitting, followed by the repair of the plasterboard, and repainting

A number of homes in the field study were constructed with concrete walls. The concrete provides minimal insulation, and the housing commission concrete homes are notoriously cold in winter. One householder commented that prior to the original installation of the central heating system, condensation would frequently form on the inner surface of the outside walls during winter, with mould accumulation. An uninsulated concrete wall achieves an R-value of approximately 0.11 m^2.K/W, compared to around 0.88 m^2.K/W for a 25 mm layer of polystyrene. Merely providing an air gap will improve the R-value significantly, and providing a reflective surface inside the cavity would improve the thermal resistance further. Some of the householders had investigated methods to insulate the homes, such as the installation of external siding, however the cost was generally prohibitive. One method that could be considered would be the fitment of narrow timberwork studs or battens (such as 45 x 45mm or smaller), or steel plasterboard framing, against the inner surface of the external walls, with plasterboard installed against the timber or steel studs. The cavity between the concrete and plasterboard could be filled with a number of insulating materials, such as reflective foil or foilboard. This would increase the thermal resistance of the walls substantially, while reducing the living space minimally. The cost of both of these options will be prohibitive for many householders, but may be reasonable in the context of a minor renovation.

Improving insulation, apart from the direct energy saving benefits, will increase the temperature of the surrounds of a room, thereby decreasing radiant heat losses from the body to the surroundings, making the room feel more comfortable for a given air temperature.

Heat transfer takes place between objects whenever there is a temperature difference between an object and its surroundings. As the body temperature of humans is around 37 ^{o}C (Elert 2008), any object that is less than 37 ^{o}C will contribute to an energy loss from the person to the object, leading to cooling of the body. The comfort level defined by Fanger (1970) includes a measure of "mean radiant temperature", which defines the aggregate effect of radiant heat, and obtaining a proportion of heat from radiant sources contributes to the overall comfort level.

One of the drawbacks of ducted heating is that it provides its "heating effect" by increasing the air temperature, without directly increasing the radiant heat. The effect of increasing the air temperature while maintaining radiant temperatures is a behavioural inclination to increase the air temperature above what would normally be considered a comfortable level, to offset the lack of radiant heat. Conversely, the impact of sufficient radiant heat is most easily observed in the middle of a cool winter day when the sun is shining. Although the air temperature may be low, a person may feel comfortable nonetheless, because of the radiant heat. Similarly, one may be comfortable in front of an open fire or wood burner because of the effect of radiant heat due to the high temperatures of the fire and surroundings. In homes with ducted heating, the radiant heating loss can be improved by increasing insulation in the walls, ceiling and floor.

It is difficult to predict the energy savings attributable to the installation of insulation in advance. However Sustainability Victoria (2008) provides a guide to expected energy savings for homes without pre-existing insulation, which is listed in table 22. Table 21 provides an estimate of costs to retrofit insulation into an average home typical of those in the field study.

Location of insulation	**Type**	**R Value**	**Cost ($/m^2)**	**Approximate cost of home ($)**
Ceiling	Poly/fibreglass batts – installed by householder	3.5	5.42	500-700
Ceiling	Poly/fibreglass batts – installed professionally	3.5	7.70	700-1000
Walls	Blown-in Bradford Fibretex loose rock wool	3.0	40.00	3000-5000

Table 19 Cost of retrofitting insulation into existing homes, including labour. Sources: Insulation Australia (2008), Construct-Ramsay (2007)

Extent of insulation	Heating
Ceiling only (added R2.5)	15-25%
Ceiling (added R2.5) and walls (added R1.0)	40-50%
Ceiling (added R2.5), walls (added R1.0) and floor (added R1.0)	45-55%

Table 20 Energy savings due to insulation in Victoria. Source: Sustainability Victoria (2008)

8.2 Gas furnace efficiency

The retail price of a popular brand of gas ducted furnace was used to analyse the costs and benefits of spending more to obtain a higher efficiency furnace. Although the higher efficiency furnaces have a higher purchase price, the lifetime running costs, assuming a reference gas usage of 58 GJ (at 80% efficiency), and 1 cent/MJ gas cost, provides lower lifetime costs. The longer the life of the equipment, the greater the difference in lifetime cost between low efficiency and high efficiency equipment.

Households that have the capital available to purchase the higher efficiency equipment will therefore benefit in the long term, with low income households being more likely to elect to purchase lower efficiency equipment. The highest efficiency gas furnaces currently available have a seasonal operating efficiency of 95%, correlating with 5.5 star. This also highlights the split incentive problem facing landlords and renters, and also builders and home purchasers, where landlords and builders' priority is usually to minimise capital costs, while householders are also trying to minimise running costs.

Anecdotal evidence suggests that the replacement market consists of mostly lower efficiency furnaces. This provides an example of the "bounded rationality" problem, where householders may make sub-optimal decisions due to imperfect information. There may be high transaction costs related to obtaining information, and a bias towards basing decisions on rules-of -thumb.

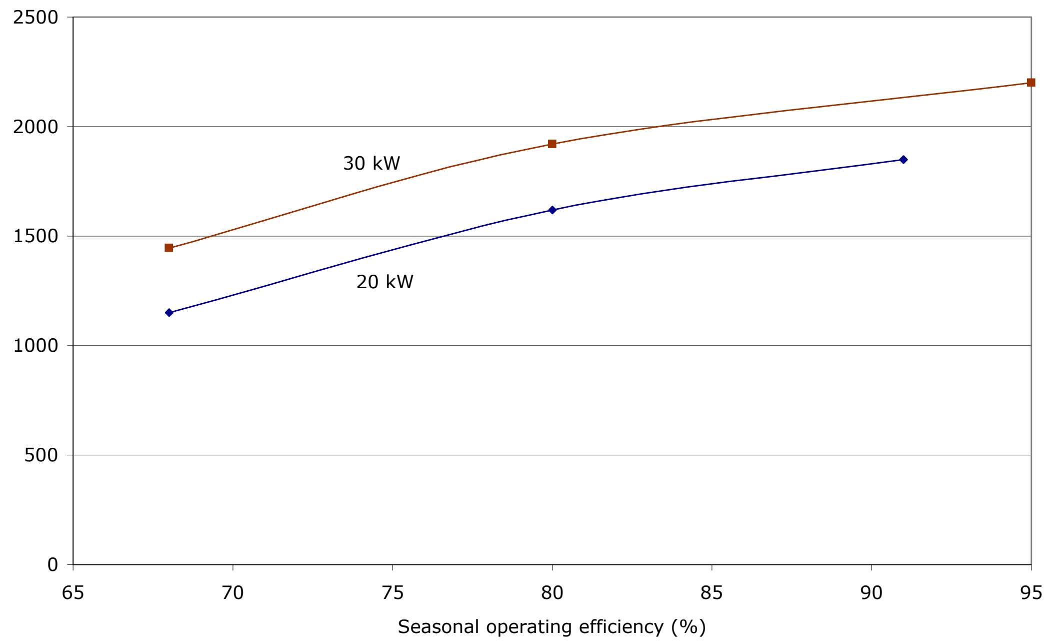


Figure 25 Retail price of a popular brand of gas ducted furnace excluding installation

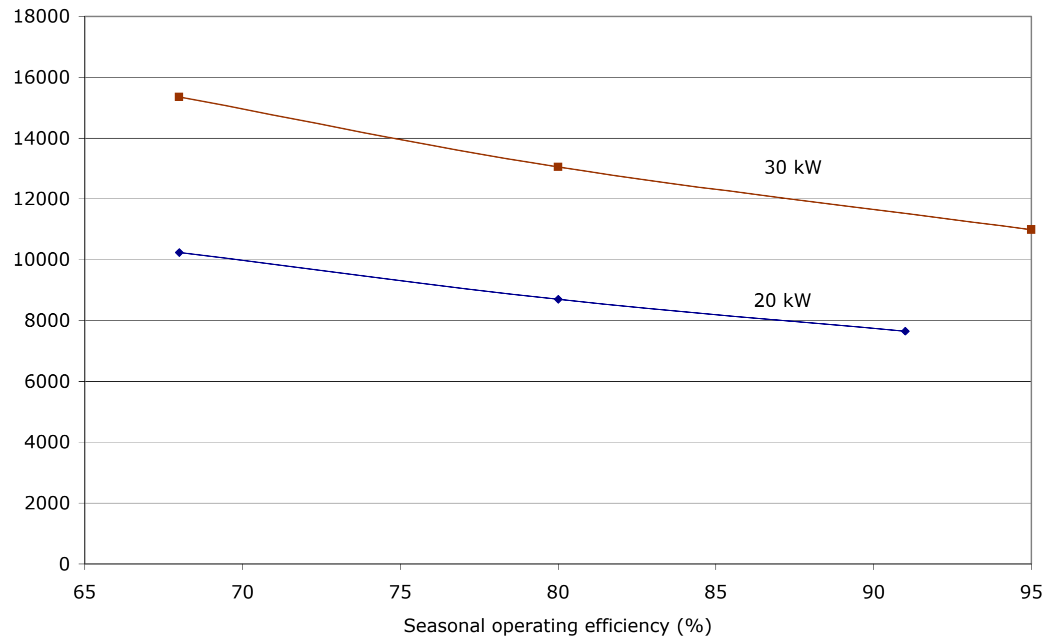


Figure 26 Lifetime cost including purchase of furnace plus gas cost over 15 years at 1 cent/MJ and average gas usage

Table 24 compares two furnaces from the same manufacturer, excluding installation costs. The simple payback period of selecting the higher efficiency furnace, in terms of the cost of energy saved is 5.4 years, based on an average 800 hours usage per annum, assuming a gas cost of 1 cent/MJ. This payback assumes that a householder has elected to purchase a furnace regardless, and is considering upgrading to a higher efficiency unit, and assumes the same installation cost. This is in contrast to making a decision as to whether an operational furnace should be replaced. In most cases, the decision will involve trade-offs between capital, maintenance and energy costs, and consideration of the likely life of existing equipment. From a lifetime perspective, it is clearly more cost effective to install higher efficiency equipment initially, rather than deciding at a later date to change operational equipment.

Seasonal operating efficiency (%)	**Furnace price ($)**	**Annual energy use (GJ)**	**Estimated energy cost over 15 years ($)**	**Energy/capital cost multiple**
95	2220	51	7648	3.4
68	1380	68	10235	7.4

Table 21 Capital cost versus energy cost of two gas furnaces, excluding installation costs, over a 15 year life, assuming average energy consumption and 1 cent/MJ gas cost.

Vattenfall (2007) provides a measurement of the cost of energy efficiency in terms of cost per tonne of CO_2-e abatement. This measure provides a direct comparison with a carbon cost, and it follows that it is economically rational to undertake the abatement measure if the cost is lower than the current and projected emissions cost. Table 25 provides a cost of abatement for the higher efficiency furnace, assuming a 15 year lifetime, a standardised 58 GJ per annum, with a reduction in annual consumption of 17 GJ, in Victoria using natural gas, without discounting. It is noteworthy that the relatively low greenhouse intensity of natural gas works against the abatement measures, in contrast to electricity.

8.3 Summary of alternative measures

Figure 26 provides an overview of the estimated costs and benefits of energy saving measures that could be implemented by a householder for a home typical of the field study; area of 110 m^2, 3 star furnace, ductwork losses of 30 percent, R1.0 ceiling insulation, no wall or floor insulation. The measures assume that doing nothing is an option. The graph assumes that the furnace is still in operational condition, but the choice of whether to upgrade the furnace to a higher efficiency unit is substantially cheaper if the unit requires replacement anyway. The payback periods are estimates based on 58 GJ of natural gas per annum at 1 cent/MJ. Circles, rather than points, have been used in the graph to indicate a range of costs and benefits.

The reduction on energy consumption relates to a single measure being implemented. If more than one measure is implemented, then additional measures would be expected to provide compounded percentage reductions, rather than simply adding the percent reduction. This means that subsequent energy saving measures will result in lower absolute energy savings, which will increase the simple payback period.

The typical furnace efficiency up to the 1990's was of the order of 70%. The installation of a high efficiency gas furnace (up to 5.5 star) will therefore provide an almost guaranteed improvement of 28 to 36 percent in energy efficiency. The installation of various types of insulation will provide both energy savings, as well as an improvement in comfort levels due to a reduction in radiant energy losses. The replacement of ductwork provides a very good trade-off between costs and benefits.

	Units	Duct replacement	Marginal cost of 2.8 star compared to 5.5 star gas furnace
Capital cost	$	1500	840
Annual energy reduction	GJ	17	17
Annual energy cost reduction	$	170	170
Amortisation period	years	15	15
Discount rate	%	7	7
Annualised capital cost	$	165	92
Net annual cost (saving)	$	(5)	(78)
Annual greenhouse abatement	tonne CO_2-e	1.1	1.1
Abatement cost	$/tonne CO_2-e	(4.9)	(72)

Table 22 Example calculations of abatement cost

Table 23 provides example calculations of two energy efficiency options, using the procedure from Vattenfall (2007). The abatement calculations provide some interesting insights. Referring to the cost of replacing ductwork, capital cost of $1,500, with an annual energy saving of $170, provides a simple payback period of 9 years. However if the capital cost is amortised over 15 years, the annual energy reduction exceeds the annualised capital cost. Combined with the greenhouse reduction, the ductwork replacement provides a negative cost of abatement of $4.9/tonne CO_2-e. The case of the marginal cost of optioning a 5.5 star gas ducted furnace in preference to a 2.8 star furnace provides a negative cost of abatement of $72 tonne CO_2-e.

Also shown on figure 26 are lines for various costs of abatement, plotted against energy reductions versus capital cost. The graph only applies for the assumptions as provided, and represents a 20 to 40 year old home typical of the field study. For newer homes, with improved insulation and equipment, the benefits would be expected to be reduced.

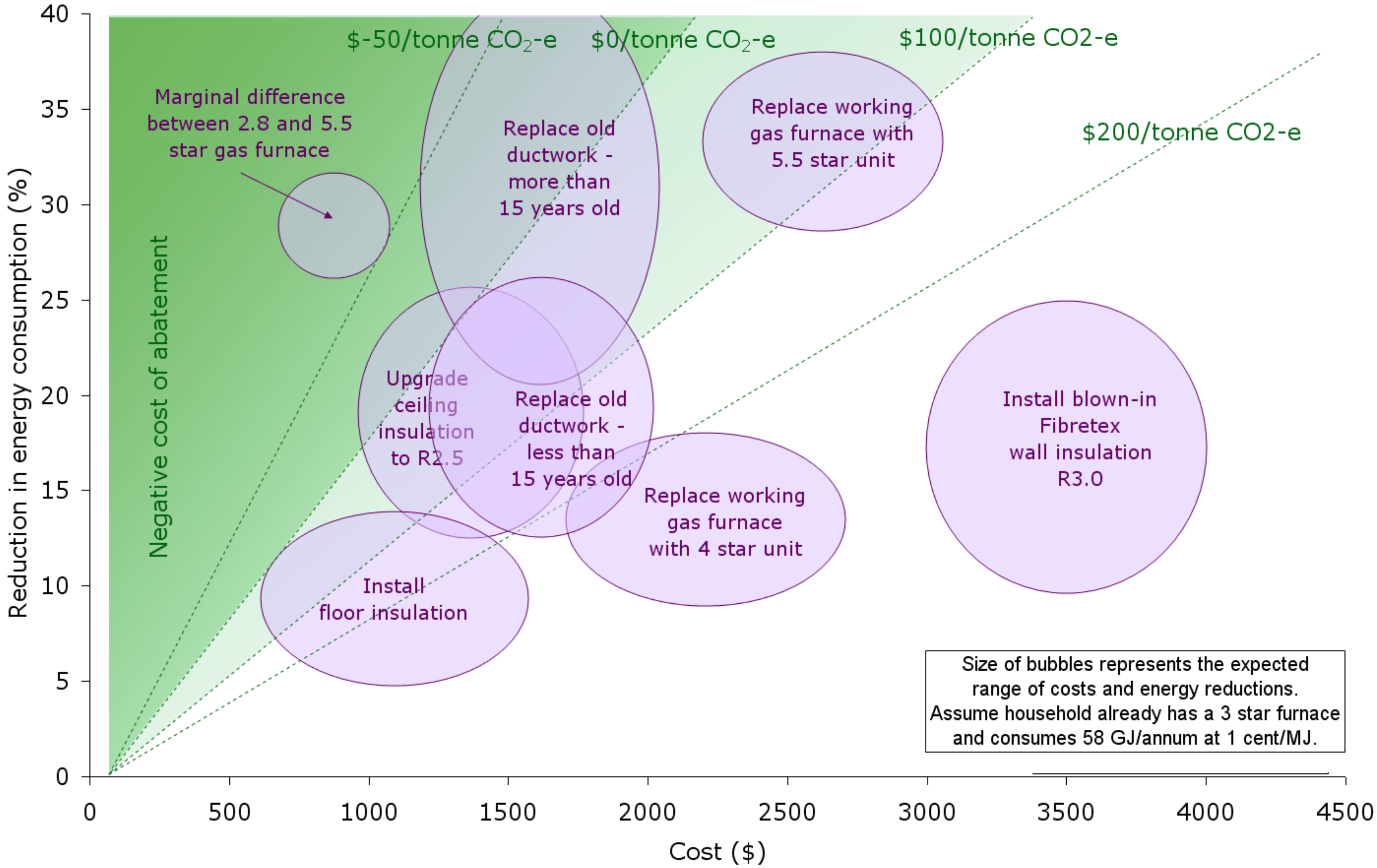


Figure 27 Comparison of energy efficiency options for 20 to 40 year old home typical of that in field study, without significant ceiling insulation. Emission abatement estimates assume amortisation over 15 years, 7% discount rate, 58 GJ per annum before energy efficiency measure, natural gas in Victoria at 1 cent/MJ

9. Conclusions and recommendations

The field study found that older Victorian gas ducted heating systems incur energy losses of 20 to 40%, which is consistent with similar studies on North American systems, and that losses consist of both leakage and thermal losses. Systems of approximately 15 years or earlier are subject to significantly less energy loss, with most of the benefit being due to a reduction in leakage losses due to improved flexible duct and fittings. However improvements in many newer systems would be possible through the upgrade of ductwork to R1.5 with insulated fittings.

The replacement of ductwork in systems older than 15 years is recommended, and would result in an average payback period of 9 years, and an average greenhouse abatement cost of $33 per tonne CO_2-e. The use of duct with a thermal rating of R1.5 incurs a higher initial cost, but would deliver a better lifetime cost benefit, and a reduction in greenhouse emissions. The replacement of the heater would be expected to achieve a similar benefit, but at a higher cost.

In comparing a number of energy reduction options available to householders with systems 15 years or older, the replacement of the ductwork provides a shorter payback period compared to other options, including additional insulation and an upgrade of the heating furnace. However it is less clear that systems that are less than 15 years old would benefit as much from ductwork replacement compared to upgrading the furnace.

Acknowledgements

Thanks to Sustainability Victoria for supporting and funding the project, especially Peter Davison, Katrina Wolfe, Robert Hines, Ian McNichol and Ken Guthrie. Thanks to Dr John Andrews and Dr Andrea Bunting for the RMIT Sustainable Energy program, Paltech Corporation for providing the facilities, equipment for the test rigs, and supply of ductwork, and Ian Curtain of Ideal Heating and Air Conditioning for performing the ductwork replacements, and thanks to the participating households for making their homes available for the field study.

References

Abbott Malcolm, 2006, *The performance of an electricity utility: the case of the State Electricity Commission of Victoria, 1925-93*, Australian Economic History Review, Vol. 46, No. 1

ABARE (Australian Bureau of Agricultural and Resource Economics), 2003, *Australian Gas Markets – Moving Towards Maturity*, <http://www.abareconomics.com/publications_html/energy/energy_03/er03_gas.pdf>, viewed 24 May 208

----- 2007, *Australian energy consumption, by industry and fuel type – energy units – tables F-F8*, <http://www.abareconomics.com/interactive/energyUPDATE08/excel/table_F_08.xls>, viewed 10 February 2008

ABC Western Australia, 8 Jan 2004, *Tuckey outlines preferred gas pipeline route*, <http://www.abc.net.au/wa/news/200401/s1022087.htm>

ABC PM, 2008, *Exxon Mobil to develop massive gas field*, <http://www.abc.net.au/pm/content/2008/s2314923.htm>, viewed 8 August 2008

ABC, 2007, *High demand expected for Gladstone LNG*, <http://www.abc.net.au/news/australia/qld/capricornia/200706/s1941339.htm>

Andrews, John, 2003, *Effect of Airflow and Heat Input Rates on Duct Efficiency*, ASHRAE Transaction; 2003;109

American Society of Heating, Refrigeration and Air-conditioning Engineers, 2004, *ANSI/ASHRAE Standard 152-2004, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*

ASHRAE Standard 55-2004, 2004, *Thermal Environmental Conditions for Human Occupancy*

AusIndustry, 2007, *Commercial Ready Grant Agreements signed in Financial Year 2006-2007 - Nova Duct Technologies Pty Ltd*, <http://www.ausindustry.gov.au/library/CommercialReadyGrantAgreementssignedin06_07_May_and_June20070807111438.pdf>

Australian Bureau of Statistics, 2002, *4102.0 Australian Social Trends*, <http://www.abs.gov.au/ausstats/subscriber.nsf/log?openagent&41020_2002.pdf&4102.0&Publication&C0A01711EAD911BFCA256BCD007D7F10&0&2002&04.06.2002&Previous>, viewed 23 June 2008

----- 2003, *1301.0 Year Book Australia – Construction and the Environment*, <http://www.abs.gov.au/Ausstats/abs@.nsf/Previousproducts/1301.0Feature%20Article282003?opendocument&tabname=Summary&prodno=1301.0&issue=2003&num=&view=>, viewed 23 June 2008

----- 2005a, *4602.0 Environmental Issues: People's Views and Practices*, <http://www.abs.gov.au/ausstats/subscriber.nsf/log?openagent&46020_mar%202005.pdf&4602.0&Publication&4B2EFD806DDA33CBCA2570C700729463&0&Mar%202005&29.11.2005&Previous>, viewed 23 June 2008

----- 2005b, *4618.4 Domestic Use of Water and Energy – South Australia*, <http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/309F7FB77CDB8130CA256FE20074B8DD/$File/46184_oct%202004.pdf>, viewed 24 August 2008

----- 2008, *Building Approvals, Australia, Apr 2008*, <http://www.abs.gov.au/AUSSTATS/abs@.nsf/featurearticlesbyCatalogue/7346835926C5D67DCA257421000F3850?OpenDocument>, viewed 23 June 2008

Australian Competition and Consumer Commission, 2006, Presentation at the *Thermal Performance of Flexible Air-Conditioning Ductwork* meeting in Melbourne 27 October 2006 chaired by the Dr Tony Marker of the Australian Greenhouse Office

Australian Department of Climate Change, 2008, *Carbon Pollution Scheme Green Paper*, <http://www.climatechange.gov.au/greenpaper/report/pubs/greenpaper.pdf>, viewed 20 July 2008

Australian Energy Regulator, 2007, *State of the Energy Market 2007*, <http://nla.gov.au/anbd.bib-an42315626>, viewed 23 June 2008

Australian Gas Association, 2007, *Directory of Certified Appliances and Components*, <http://www.aga.asn.au/uploads/148/2007_03.pdf>, viewed 23 June 2008

Australian Greenhouse Office, 1999, *Australian Residential Building Sector Greenhouse Gas Emissions 1990-2010*, <http://www.greenhouse.gov.au/buildings/publications/pubs/final_report.pdf>, viewed 23 June 2008

----- 2003, *Life Cycle Assessment of Greenhouse Emissions from Domestic Woodheating*, <http://www.greenhouse.gov.au/nrm/publications/pubs/firewood.pdf>, viewed 23 June 2008

----- 2004a, *Air-conditioning and MEPS Workshop*

----- 2004b, *Minimum Energy Performance Standards – Heat pumps*, <http://www.energyrating.gov.au/library/pubs/200417-mepsheatpumps.pdf>, viewed 26 May 2008

----- 2005, *Switch on Gas - Australia's strategy to improve the energy efficiency of gas appliances and equipment 2005–2015*, <http://www.energyrating.gov.au/library/pubs/200419-switchongas.pdf>, viewed 23 June 2008

----- 2007, *Greenhouse emission calculator*

Baird, G., Alcorn, A., Haslam, P., 1997, *The Energy Embodied in Building Materials – updated New Zealand Coefficients and their significance*, IPENZ Transactions, Vol. 24., No. 1/CE, 1997

Boe A.B., 1998, *Impacts of Forced Air Distribution Systems on Homes and Potential for Improvements*, Report #98-004, Northwest Energy Efficiency Alliance, Oregon

California Energy Commission, 2005, *2005 Building Energy Standards – Residential Compliance Manual*, <http://www.energy.ca.gov/2005publications/CEC-400-2005-005/CEC-400-2005-005-CMF.PDF>, viewed 20 June 2008

------ 2007, *Natural Gas Market Assessment ; Preliminary Results*, < http://www.energy.ca.gov/2007publications/CEC-200-2007-009/CEC-200-2007-009-SD.PDF>, viewed 20 June 2008

Construct-Ramsay, 2007, Personal communication regarding blow-in insulation phone 9561 3455

Cox-Smith Ian, 2006, *Branz - Proposed Flexible Ducting Test Methodology*, Presentation at the Thermal Performance of Flexible Air-Conditioning Ductwork meeting in Melbourne 27 October 2006 chaired by the Australian Greenhouse Office

Dey Iain, 9 March 2008, *Times Online - Price war threat to UK gas supplies*, <http://business.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article3510672.ece>, viewed 23 June 2008

Diesendorf Mark, 2007, *Greenhouse Solutions with Sustainable Energy*, UNSW Press

Donnelly W.J., 2003a, *US Patent Application 2003018879, Duct and Method of Construction*, <http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&u=%2Fnetahtml%2FPTO%2Fsearch-adv.html&r=1&p=1&f=G&l=50&d=PG01&S1=20030188792.PGNR.&OS=dn/20030188792&RS=DN/20030188792>, viewed 18 May 2008

Donnelly W.J., 2003b, *US Patent Application 20030098586, Duct Joiner and Method of Manufacture,* <http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&u=%2Fnetahtml%2FPTO%2Fsearch-adv.html&r=1&p=1&f=G&l=50&d=PG01&S1=20030098586.PGNR.&OS=dn/20030098586&RS=DN/20030098586>, viewed 23 June 2008

Donnelly W.J., 2008, *US Patent Application 20080041483, Duct and Method of Construction*, <http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&u=%2Fnetahtml%2FPTO%2Fsearch-adv.html&r=1&f=G&l=50&d=PG01&p=1&S1=20080041483.PGNR.&OS=dn/20080041483&RS=DN/20080041483>, viewed 18 May 2008

Driscoll Don, Milkovits George, Freudenberger David, 2000, *Impact and use of Firewood*, <http://www.environment.gov.au/land/publications/firewood-impacts/pubs/firewood-impacts.pdf>, viewed 24 July 2008

Earth to Air Systems, 2008, *System specification brochure - Deep well Direct Exchange Geothermal Heating and Cooling*

Edwards, C., 1969, *Brown Power – A Jubilee History of the State Electricity Commission of Victoria*, The Griffin Press, Adelaide

Elert Glenn, 2008, *Temperature of a Healthy Human (Body Temperature)*, <http://hypertextbook.com/facts/LenaWong.shtml>, viewed 12 August 2008

Energy Efficient Strategies, 2008, *Energy Use in the Australian Residential Sector 1986-2020*, <http://www.environment.gov.au/settlements/energyefficiency/buildings/publications/energyuse.html>, viewed July 2008

Energy Networks Association, 2007, *State Overviews*, <http://www.ena.asn.au/webc/factsandfigures/?0,0,a001,247>, viewed 10 Dec 2007

Energy Performance of Buildings Directive, 2008, *EU Energy Performance of Buildings*, <http://www.diag.org.uk/>, viewed 17 September 2008

Energy Safe Victoria, 2007, *Natural Gas in Victoria*, <http://www.esv.vic.gov.au/ForConsumers/OverviewofgasindustryinAustralia/NaturalgasinVictoria/tabid/295/Default.aspx>, viewed 23 June 2008

Essential Services Commission Victoria, 2007, *Gas Access Arrangement Review 2008-2012 - Draft Decision*, <http://www.esc.vic.gov.au/NR/rdonlyres/BBCD6D49-4BE3-4525-8AA5-883B2777667F/0/20070904OTHDraftdecisionGAAR200812.pdf>

Fanger P O, 1970, *Thermal Comfort*, Danish Technical Press

Francisco Paul W., Palmiter Larry, Davis Bob, 1998a, *Modeling the thermal distribution efficiency of ducts: comparisons to measured results*, Energy and Buildings 28 (1998) 287-297

----- 1998b, *Measured and Modeled Duct Efficiency in Manufactured Homes: Insights for Standard 152P*, ASHRAE Transactions;1998; 104

Fricker, James, 1997, *Enersonics - Report on Thermal Performance of Flexible Ducts for Westaflex*

Fricker James, Johnson Dr Peter, *Testing and Modelling of Flexible Air Duct Heat Losses*

Gallop G., 2005, Speech given at Perth Convention and Exhibition Centre 11 April 2005, <http://www.premier.wa.gov.au/docs/speeches/110405_APPEA_conference.pdf>, viewed 10 Dec 2007

Gas and Fuel Corporation of Victoria, 1990, *High Efficiency Gas Appliance Penetration and Gas Savings in Victoria,* Gas Demand Management Discussion Paper No 5, Economic Policy and Research Department, Melbourne

George Wilkenfeld & Associates, 2004a, *Gas Appliance and Equipment Energy Efficiency Program (GAEEEP) - OUTLINE STRATEGIC PLAN*, <http://www.sv.sustainability.vic.gov.au/ftp/energy_efficiency/gas_meps/GAEEEP_Outline_Strategic_Plan.pdf>, viewed 10 Dec 2007

------ 2004b, *A National Demand Management Strategy for Small Airconditioners*, National Appliance and Equipment Energy Efficiency Committee

----- 2007, *Options to reduce greenhouse emissions from new homes in Victoria through the building approval process*, <http://www.greenhouse.vic.gov.au/CA256F310024B628/0/F11562D1933137F7CA2572E2001C5060/$File/5_star+energy+report+May+07+.pdf>, viewed 1 September 2008

Harris, Michael, 2006, *Use the Sun to Heat the House*, ReNew Magazine, Apr-Jun 2006

Insulation Australia, 2008, *Services for Home Insulation*, <http://www.insulationaustralia.com.au/homeowner.asp>, viewed 10 Dec 2007

IPART, 2001, *Review of the Delivered Price of Natural Gas to Low-Usage Customers Served by Country Energy*, <http://www.iprt.net/pdf/Gas01-07.pdf>, viewed 7 April 2008

Jump D., Walker I., Modera M., 1996, *Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems*, Lawrence Berkeley National Laboratory, Proc. ACEEE Summer Study 1996

Lawrence Berkeley National Laboratory, 2008, *Aerosol Duct Sealing*, <http://eetd.lbl.gov/l2m2/aerosol.html>

Levinson R.M., Delp, W., Dickerhoff, D.J., Modera, M.P., 2000, *Effects of Air Infiltration on the Effective Thermal Conductivity of Internal Glass wool Insulation and on the Delivery of Thermal Capacity Via Ducts*, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory

Lewis R., Goldman M., Farmer R., 2007, *Report to the Joint Working Group on Natural Gas Supply*, <http://www.mce.gov.au/assets/documents/mceinternet/MMA%20Final_Report_to_the_Joint_Working_Group_on_Natural_Gas_Suppley(July2007)20071008161704.pdf>, viewed 18 August 2008

Macdonald-Smith Angela, 2008, *Bloomberg - First of World's Largest LNG Tankers to Be Delivered by Summer*, <http://www.bloomberg.com/apps/news?pid=20601082&sid=atfXujtneXO8&refer=canada>, viewed 23 June 2008

Metropolitan Fire Brigade (Melbourne), 2002, *Dusty Ducts*, <http://www.mfb.vic.gov.au/default.asp?casid=307>, viewed 10 July 2008

Meyer, W. B., 2002, *Why Indoor Climates Change: A Case Study*, Climatic Change 55:395-407

Modera Mark, 1993, *Characterising the performance of residential air distribution systems*, Energy and Buildings 20 (1993) 65-75

------ 2005, *ASHRAE Standard 152 & Duct Leaks in Houses*, ASHRAE Journal March 2005

Morse, 1988, *Technology in Australia 1788-1988 – Energy*, <http://www.austehc.unimelb.edu.au/tia/778.html>, viewed 26 April 2008

Murphy, Mathew, 2008, *The Age Business Day 7 June 2008 - Is Gas the New Black?*, <http://business.theage.com.au/is-gas-the-new-black-20080606-2mz5.html>, viewed 7 June 2008

National Appliance and Equipment Energy Efficiency Committee, 2004, *Gas Space Heaters – Australia's Standby Power Strategy 2002-2014*, <http://www.energyrating.gov.au/library/pubs/sb200417-gasheaters.pdf>, viewed 16 July 2008

Novaduct, 2008, *Novaduct Innovations*, <http://www.austrellgroup.com.au/novaduct.asp>, viewed 10 July 2008

NSW EPA, 2007, *Information about assessing gasworks sites*, <http://www.environment.nsw.gov.au/clm/gasworksassessment.htm>, viewed 26 April 2008

NSW, 2007, *Information about generating town gas*. <http://www.environment.nsw.gov.au/clm/gasworksassessment.htm>, viewed 26 April 2008

Origin Energy, 2008, *Origin Energy Natural Gas Prices for Deemed and Standing Offer Contracts*, <http://www.originenergy.com.au/postcode/?_qf_p2_display=true&connection_type=H&fuel_type=G&postcode=3131&state=VIC>, viewed 23 June 2008

Pears Alan, 1998a, *Energy-Efficient Environmentally-Preferable Gas Appliances for a Sustainable World*, Presented at Aust Gas Association Annual Conference, Adelaide November 1998

----- 1998b, *Strategic Study of Household Energy and Greenhouse Issues*, <http://www.energyrating.gov.au/library/pubs/pears-ago1998.pdf>, viewed 6 July 2008

----- 2007a, *Submission to Inquiry into the National Market Driven Energy Efficiency Bill*, <http://www.aph.gov.au/SENATE/committee/economics_ctte/energy_efficiency2007/submissions/sub2.pdf>, viewed 26 August 2008

------ 2007b, *Retrofitting Wall Insulation*, ReNew Magazine, Jan-March 2007

------ 2008, *National Market Driven Energy Efficiency Target Bill 2007 [2008] and Renewable Energy Legislation Amendment (Renewable Power Percentage) Bill 2008 - Interaction between MRET, Energy Efficiency and Emissions Trading Scheme*, <http://www.aph.gov.au/SENATE/COMMITTEE/economics_ctte/nmdeet_08/report/index.htm>, viewed 28 August 2008

Pellet Heaters Australia, 2008, *EF2*, <http://www.pelletheaters.com.au/ef2.html>, viewed 23 June 2008

Pipeline & Gas Journal, 2006, *Pipeline & Gas Journal's 2006 International Pipeline Construction Report 2006*, <http://www.pipelineandgasjournal.com/PGJ/pgj_archive/August06/pipelineconstreport.pdf>, viewed 26 April 2008

Plambeck, James, 1996, *The Fuel Industry: Wood, Coal, and Domestic Gas*, <http://www.intute.ac.uk/sciences/reference/plambeck/chem1/p01264a.htm>, viewed 26 April 2008

National Plumbing Regulators Forum, 2004, *Plumbing Code of Australia*

Plumbing Industry Commission, 2005, *Thermal Insulation of Central Heating*, <http://www.pic.vic.gov.au/resources/documents/Thermal_insulation_of_central_heating.pdf>, viewed 23 June 2008

Productivity Commission, 2005, *The Private Cost Effectiveness of Improving Energy Efficiency*

Proudley Ray, 1987, *Circle of Influence. A History of the Gas Industry in Victoria*, Margren Publishing with the Gas and Fuel Corporation of Victoria. Melbourne 1987

Roberts, A., Harman, J., 2002, *Economics of retail competition in Australia's natural gas industry*, Australian Bureau of Agricultural and Resource Economics 46th Annual Conference of the Australian Agricultural and Resource Economics Society Canberra, 12–15 February 2002, <http://www.abareconomics.com/publications_html/conference/conference_02/CP02_03.pdf>, viewed 7 April 2008

Roarty, Mike, 2008, *Australia's Natural Gas: Issues and Trends*, Parliamentary Library Research Paper no. 25 2007-08, <http://www.aph.gov.au/library/pubs/rp/2007-08/08rp25.htm>, viewed 20 June 2008

Schroeder et al., 1965, *US Patent 3216459 - Flexible Insulated Duct*, <http://patimg2.uspto.gov/.piw?Docid=03216459&homeurl=http%3A%2F%2Fpatft.uspto.gov%2Fnetacgi%2Fnph-Parser%3FSect1%3DPTO2%2526Sect2%3DHITOFF%2526u%3D%25252Fnetahtml%25252FPTO%25252Fsearch-adv.htm%2526r%3D1%2526p%3D1%2526f%3DG%2526l%3D50%2526d%3DPALL%2526S1%3D3216459.PN.%2526OS%3Dpn%2F3216459%2526RS%3DPN%2F3216459&PageNum=&Rtype=&SectionNum=&idkey=NONE&Input=View+first+page>, viewed 18 May 2008

Sherman M., 2001, In part of a submission to: *Public hearing before the California Energy Resources Conservation and Development Commission - In the matter of: 2001 Building Energy Efficiency Standards - Duct Tape - AB-970*

Sherman Max, Walker Ian, 1998, *Can Duct Tape take the Heat*, <http://epb.lbl.gov/publications/lbl-41434.pdf>, viewed 10 July 2008

Short C., Heaney A. and Burns K., 2003, *ABARE: Australian Gas Markets: Moving Towards Maturity*, <http://www.abareconomics.com/publications_html/energy/energy_03/er03_gas.pdf>, viewed 20 June 2008

Sustainability Victoria, 2005, *Training Needs Analysis HVAC designers and Installers Forum Record*, <http://www.nfee.gov.au/public/download.jsp?id=562>

Shove Elizabeth, 2007, *Comfort and Convenience in the Home*, <http://www.abc.net.au/rn/bydesign/stories/2007/1981781.htm>, viewed 23 June 2008

St Kilda Historical Society, 2007, *Former Gas Valve House - 617 St Kilda Road, Melbourne*, <http://www.skhs.org.au/SKHSbuildings/47.htm>, viewed 23 June 2008
Sustainable Energy Authority Victoria, 2003, *Driving Energy Efficiency Improvements to Domestic Gas Appliances*, <http://www.energyrating.gov.au/library/pubs/2003-gasdiscussionpaper.pdf>, viewed 26 April 2008

----- , *Insulation benefits*, <www.sustainability.vic.gov.au/resources/documents/Insulation_benefits.pdf>, viewed 1 June 2008

Sun Lizard, 2008, *Sun Lizard frequently asked questions*, <http://www.sunlizard.com.au/content/solarclimatecontrolfaq.html>, viewed 23 June 2008

Sydney Morning Herald, 2006, *Transcontinental gas pipe a possibility*, <http://www.smh.com.au/news/BUSINESS/Transcontinental-gas-pipe-a-possibility/2006/06/07/1149359804300.html>, viewed 26 April 2008

Sydney Morning Herald, 2004, *Big Stink in Gasland*, <http://www.smh.com.au/articles/2004/01/09/1073437472720.html>, viewed 26 April 2008

Todd John, 2003, *Wood-Smoke Handbook: Woodheaters, Firewood and Operator Practice*, <http://www.environment.gov.au/atmosphere/airquality/publications/handbook/pubs/woodsmoke-handbook.pdf>, viewed 21 August 2008

----- 2006, *2005 Australian Firewood Costs and Woodheater Running Costs*

----- 2008, *ABC Radio National - Australia Talks - Wood fired heating*, <http://www.abc.net.au/rn/australiatalks/stories/2008/2299161.htm> and <http://mpegmedia.abc.net.au/rn/podcast/current/audioonly/ats_20080715.mp3>

Treidler, B. and Modera M., 1994, *Thermal Performance of Residential Duct Systems in Basements*, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California

Treloar G., Fay R., Love P.E., Iyer-Raniga U., 2000, *Analysing the life-cycle of an Australian residential building and its householders*, Building Research & Information (2000) 28(3), 184-195

Treloar G., Fay R., Love P.E., Iyer-Raniga U., 2000, *Life-cycle energy analysis of buildings: a case study*, Building Research & Information (2000) 28(1), 31-41

UK Department of Trade and Industry, 2007, *Meeting the Energy Challenge : A White Paper on Energy*, <http://www.berr.gov.uk/energy/whitepaper/page39534.html>, viewed 26 April 2008

Vattenfall, 2007, Global Mapping of Greenhouse Gas Abatement Opportunities up to 2030 - Buildings sector deep-dive, <http://www.vattenfall.com/www/ccc/ccc/Gemeinsame_Inhalte/DOCUMENT/567263vattenfall/P0272861.pdf>, viewed 28 August 2008

Victorian Auditor General, 1997, *Report of the Auditor-General on the Government's Annual Financial Statement 1996-97*, <http://www.audit.vic.gov.au/old/sfo97/sfo9707.htm>, viewed 26 April 2008

Vulcan, 1981, *Ventilation Duct Boot Assembly*, <http://pericles.ipaustralia.gov.au/aub/pdf/1981/0103/198172172A1/198172172.pdf>, viewed 6 August 2008

Walker, I.S. Wray, C.P., 2003, *Evaluation of Flow Capture Techniques for Measuring HVAC Grille Airflow*s, Ernest Orlando Lawrence Berkeley National Laboratory, <http://www.osti.gov/bridge/servlets/purl/791782-L4bxqQ/native/791782.PDF>, viewed 26 April 2008

World Resources Institute, 2008, *Total Greenhouse Gas Emissions in 2000*, <http://cait.wri.org/cait.php?page=yearly&mode=view&sort=pc-desc&pHints=shut&url=form&year=2000&sector=natl&co2=1&ch4=1&n2o=1&pfc=1&hfc=1&sf6=1&update=Update>, viewed 28 August 2008

Yarbrough. D., 1991, *Thermal Resistance of Air Ducts with Bubblepack Reflective Insulation*, Journal of Building Physics 1991;15;137

Youle, 1995, *The Thermal Environment - from Occupational Hygiene*, <http://books.google.com.au/books?id=gHkpfWcDGvsC>, viewed 26 April 2008