GAS COOLING STUDY

PREPARED FOR:

The CANMET Energy Technology Centre (CETC)
Energy Technology Branch, Energy Sector
Department of Natural Resources Canada
Ottawa, Ontario, Canada, K1A 0E4
DSS Contract No. 23440-90-9145
November 1991

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Reprint: March 21, 2001

CITATION

Enbridge Consumers Gas, *Gas Cooling Study.* Prepared under DSS Contract No. 23440-90-9145. The CANMET Energy Technology Centre, (CETC) Energy Technology Branch, Energy Sector, Department of Natural Resources Canada, Ottawa, Ontario, 1991. (106 pages)

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Department of Natural Resources Canada
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Catalogue No. M91-7/164-1991E
ISBN 0-662-19349-0

FOREWORD

This study has the objective of evaluating the potential of natural gas-fired space cooling of buildings in Canada. This technology is not new, but several factors have combined to stimulate such a study. These factors include recent technical advances in gas-fired equipment availability, performance and costs. Additionally, the deregulation of the gas industry and the new stress on demand-side management of electrical supply in several Provinces, plus the increasing requirement for summer cooling has prompted a fresh look at the technology. The approaching phaseout of CFC production has heightened interest in alternatives to electrically-driven vapour compression cooling technology. Cogeneration and absorption cooling are also being reexamined under these changing conditions. The environmental aspects of gas-fired cooling also needed to be clarified.

Energy, Mines and Resources Canada represented by the Buildings Group of the Energy Efficiency Division, Efficiency and Alternate Energy Technology Branch negotiated a Science Contract with Consumers Gas to implement a cost-shared agreement totalling $ 50 000. Previous studies by Consumers Gas were made available to the study team as well as the results of field trials and contacts with other gas utilities, research organizations and equipment suppliers. A subcontract was negotiated with Caneta Research Inc. of Mississauga to perform the technical evaluation with Terry Whitehead of Consumers Gas acting as the Project Manager and Edward Morofsky of Energy, Mines and Resources acting as the Scientific Authority. Caneta Research Inc., led by Doug Cane, performed the state-of-the-art, the environmental assessment, the building simulations, the economic assessments and wrote the report.

The report contains a comprehensive Introduction summarizing the methodology and the findings of the study. Appendices are included dealing with technology evaluation, comparison of cooling options under some typical Canadian conditions, an environmental impact of gas cooling and a description of currently available equipment. These Appendices were contract deliverables and are self-contained studies. The report is offered as a short, but comprehensive, overview of the present technical and economic status of gas cooling supported by detailed information contained within the Appendices.

The incremental cost of gas-fired equipment ranges from $400 to $500 per ton of chilling capacity. This incremental first cost is balanced by avoided energy and demand charges for electrically-driven chilling equipment. The report focuses on larger buildings located in Toronto. These buildings not only experience a large cooling load, but also have some of the highest electrical rates in Canada. This generating electricity is a consideration, but it is difficult to evaluate fully in the case of nuclear or coal-burning plants. As well, perhaps the future electrical generating capacity should be stressed. This would be simplest in the case of future gas-fired generating capacity. While this is an interesting aspect of gas cooling, it was not considered in this work as it has been analyzed in detail by others. This report provides the basic technical data needed to evaluate gas cooling under specific conditions.

A result of this initial collaboration on the evaluation of gas cooling is the joint funding of a gas-fired, engine-driven demonstration at Trent University. This will be the first large scale evaluation of this technology in Canada. Also Energy, Mines and Resources Canada has decided to cosponsor a national workshop gathering the main players in the field of gas cooling to stimulate awareness of its potential.

AVANT-PROPOS

La présente étude vise à évaluer les possibilités de climatisation des locaux au gaz naturel au Canada. Cette technologie n'est pas nouvelle, mais plusieurs facteurs se sont conjugués pour favoriser son étude. Notons les progrès techniques récents en matière de disponibilité, de rendement et de coût des appareils au gaz; en outre, la déréglementation de l'industrie du gaz ajoutée au problème récent de la gestion de la demande d'électricité dans plusieurs provinces, ainsi que le besoin croissant de climatisation en été ont incité à jeter un nouveau regard sur la technologie. L'arrêt prochain de la production de CFC a suscité un intérêt accru pour les solutions de remplacement à la technologie de la climatisation par compression de vapeur à partir d'électricité. La climatisation par coproduction et par absorption d'énergie est re-examinée à la lumière de ces conditions changeantes. Les aspects environnementaux de la climatisation au gaz devaient aussi être clarifiés.

Énergie, Mines et Ressources Canada, représenté par le Groupe du bâtiment de la Division de l'efficacité énergétique, Direction de l'efficacité énergétique et des énergies de remplacement, a négocié un contrat scientifique avec Consumers Gas pour mettre en oeuvre une entente à frais partagés totalisant 50 000 $. Des études antérieures de Consumers Gas ont été mises à la disposition de l'équipe d'étude, ainsi que les résultats d'essais sur le terrain et de communications avec d'autres sociétés gazières, organismes de recherche et fournisseurs de matériel. Un sous-contrat a été accordé à Caneta Research Inc. de Mississauga pour faire l'évaluation technique; Terry Whitehead de Consumers Gas dirige le projet et Edward Morofsky d'Énergie, Mines et Ressources est l'autorité scientifique. Caneta Research, avec à sa tête Doug Cane, a réalisé l'évaluation environnementale qui est poussée, les simulations des bâtiments et les évaluations économiques, et a préparé le rapport.

Le rapport comprend une introduction détaillée qui résume la méthode de travail et les résultats de l'étude. Les annexes portent sur l'évaluation de la technologie, la comparaison de possibilités de climatisation dans certaines conditions canadiennes types, l'incidence de la climatisation au gaz sur l'environnement et une description du matériel actuellement disponible. Ces annexes, réalisées à forfait, sont des études complètes en soi. Le rapport a la forme d'un aperçu, bref mais complet, de l'état technique et économique actuel de la climatisation au gaz, étayé d'information détaillée contenue dans les annexes.

Le coût additionnel du matériel fonctionnant au gaz varie de 400 à 500 $ par tonne de capacité frigorifique. Ce premier coût additionnel est compensé par la non-utilisation de matériel électrique de climatisation (économies d'énergie et de frais liés à la demande pour ce matériel). Le rapport traite surtout de gros immeubles de Toronto. Ces immeubles présentent non seulement une grande charge de climatisation, mais aussi les tarifs d'électricité les plus éléves au Canada. Ils se prêteraient donc bien à une climatisation économique au gaz.

Les coefficients de performance des matériels au gaz et à l'électricité devraient être comparés dans le détail, en gardant à l'esprit que l'électricité est une forme énergétique secondaire produite par une variété de centrales tant thermiques, hydroélectriques que nucléaires. Le rendement du système de production d'électricité est un facteur à considérer, mais il est difficile à évaluer pleinement dans le cas des centrales nucléaires ou au charbon. En outre, il faudrait peut-être mettre l'accent sur la capacité future de production d'électricité. Le cas le plus simple est celui de la capacité future de production du matériel au gaz. Même s'il s'agit là d'un aspect intéressant de la climatisation au gaz, il n'a pas été abordé dans le présent travail parce que d'autres ont analysé abondamment le sujet. Le présent rapport renferme les données techniques de base pour évaluer la climatisation au gaz dans des conditions particulières.

Un des résultats de ce premier effort de collaboration pour évaluer la climatisation au gaz est le parrainage mixte d'une démonstration d'un climatiseur entraîné par un moteur à gaz à l'Université de Trent. Il s'agira de la première grande évaluation de cette technologie au Canada. De plus, Énergie, Mines et Ressources Canada a décidé de coparrainer un atelier national qui réunira les principaux intervenants dans le domaine de la climatisation au gaz pour en faire ressortir les possibilités.

Executive Summary

This report presents the results of an investigation of the state-of-the-art of gas-fired cooling equipment and applications. Emphasis was placed on the performance, electric load reduction potential, costs and benefits and relative environmental impact of cooling technologies in residential and commercial buildings in Canada.

Gas-fired cooling equipment was found to be most attractive in large office buildings, where electrical building demand is due primarily to cooling operation. Combination gas and electric cooling plants exhibit the most attractive payback periods.

Gas cooling equipment offers significant load-levelling benefits to summer peaking electric utilities and winter peaking gas utilities. Utility grants or incentives are therefore warranted to encourage the more promising gas cooling applications.

Gas cooling equipment, compared to electric cooling equipment, can be environmentally attractive, in terms of reduced ozone depletion and lower overall greenhouse gas emissions. The greenhouse gas reduction was found to be greatest in regions where a high percentage of the electricity was produced by fossil-fuel-fired generation. In other regions with large amounts of nuclear or hydraulic power generation, electric cooling systems had lower greenhouse gas emissions.

A wide range of equipment is available on the market and more promising developments are on the way. The emphasis in the latter developments is improvements in cycle efficiencies to allow the gas cooling equipment to better compete with electric cooling equipment.

Combination gas and electric cooling plants should be investigated further. Other building types other than offices may offer more attractive opportunities for gas-cooling or combination systems. Other building types which should be investigated are large retail stores, restaurants and fast-food outlets, all characterized as having electric peaks due to electric cooling. Promising systems not thoroughly investigated here are those involving desiccant dehumidification and combinations of desiccant and electric cooling equipment.

Sommaire

Ce rapport presente les resultats d'une etude des technologies de pointe et de leur applications, dans le domaine de la climatisation avec des equipements alimentes au gaz naturel. Les performances, le potentiel de reduction de la demande electrique, les couts, les benefices et l'impact relatif sur l'environnement de ces technologies de refroidissement ont ete particulierement etudies dans les secteurs residentiels et commerciaux canadiens.

Les equipements de climatisation alimentes au gaz naturel ont ete trouve les plus avantageux dans les grands edifices commerciaux ou la demande electrique est principalement due aux besoins de refroidissement. Les systemes associant des equipements de climatisation au gaz naturel et electrique montrent des couts de revient des plus interessants.

Les equipements de climatisation alimentes au gaz naturel offrent d'importants benefices simultanement aux compagnies electriques afin de reduire leur pointe de demande en ete et aux compagnies de gaz afin d'augmenter la leur en hiver. Des subventions et des aides financieres sont ainsi recommandees afin de promouvoir les applications les plus prometteuses.

Les appareils de climatisation au gaz naturel, compares a ceux electriques, peuvent etre attractifs du point de vue de l'environnement; avec une reduction de la destruction de la couche d'ozone et d'une baisse de la production generale des gaz provoquant l'effet de serre. Cette derniere remarque s'est averee plus importante dans les regions ou l'electricite est produite principalement dans des centrales thermiques a energies fossiles. Dans les autres regions ou les centrales nucleaires ou hydrauliques sont predominantes, les equipements electriques de climatisation ont une production moindre des gaz provoquant l'effet de serre.

Une grande variete d'equipement est actuellement disponible sur le marche et d'autres encore plus prometteurs sont en cours de developpement. L'effort est fait dans le developpement de ces derniers pour ameliorer les rendements afin que les appareils au gaz naturel puissent mieux rivaliser avec les appareils electriques.

Les systemes qui associent les equipements au gaz naturel et electriques devraient etre etudies plus en detail. D'autres types d'edifices, autres que commerciaux, pourraient offrir plus d'opportunites a l'installation d'equipements au gaz naturel, ou combines avec ceux electriques. Les autres types d'edifices qui devraient etre etudies sont les grands magasins de detail, les restaurants et les fast-food; tous caracterises par des pointes de demande electrique dues aux besoins de refroidissement. Les systemes prometteurs qui n'ont pas ete completement etudies dans ce rapport sont ceux qui impliquent la deshumidification par dessication et les equipements de refroidissement combinant les principes electriques et dessicatifs.

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OVERVIEW OF GAS COOLING

1. INTRODUCTION

At the present time, electricity is the overwhelming fuel choice for air conditioning of commercial and residential buildings in Canada. Whether the equipment is heat pump, air conditioner or chiller, with very few exceptions, cooling applications invariably involve vapour compression, refrigeration units powered by electrically-driven compressors.

Gas-fired cooling equipment has been manufactured for several decades and has enjoyed some success in certain cooling markets. Gas-fired ammonia-water absorption residential air conditioners were sold by several manufacturers in North America throughout the 1950's and 1960's. By the mid-1970's more than 400,000 units had been sold in North America. Yet due to reliability problems and natural gas curtailments, the market for these products eroded in the late 1970's, although a number of units are still in operation.

Today the gas-fired lithium-bromide-water absorption commercial air conditioners and chillers are very popular in Japan. Most of the equipment is also manufactured in Japan, with only limited application in North America. The limited application, in the past, was due to higher first cost and maintenance costs and because the electric chillers had much higher standard efficiencies than the best double-effect, gas-fired absorption chillers.

There are, however, a number of influencing factors which could now positively impact on the potential for gas cooling in Canada. These are:

- recent introduction of double-effect absorption and engine-driven cooling equipment in North America, with more competitive first cost and improved performance;
- the increased cost of electrical energy relative to natural gas and the need to demand-side manage electric utility peaks in Ontario and other provinces;
- the environmental concern with greenhouse gas production in utility generation;
- the phased elimination of CFCs, and discussion of the same for HCFCs, as refrigerants for cooling equipment.

This report presents the findings from a recent investigation of the state-of-the-art of gas-fired cooling equipment and applications. Particular emphasis was placed on the performance, electric load reduction potential, relative economics of this equipment for application in buildings, and environmental benefits in Canada.

For the more serious reader interested in the subject of gas-fired cooling technology, a five part Appendix, which was prepared during this investigation, is included and organized as follows:

- Appendix A: State-of-the-Art of Gas-Fired Cooling Technology Development;
- Appendix B: Update on Gas-Fired Cooling Technology Developments;
- Appendix C: Performance and Economic Attractiveness of Gas Cooling Compared to Electric Cooling in Canadian Buildings;
- Appendix D: Environmental Impact of Gas Cooling Technologies;
- Appendix E: Commercially Available Gas-Fired Cooling Equipment.

2. GAS-FIRED COOLING EQUIPMENT

There are three basic types of gas-fired cooling equipment. This section will describe how they work, their performance, their availability and current status of other developments.

2.1 TYPES OF GAS COOLING EQUIPMENT

Absorption cooling equipment contains a fluid pair such as ammonia-water or lithium-bromide-water. One of the fluids is an absorbent, the other is the refrigerant. The refrigerant vaporizes in the evaporator and is absorbed by the absorbent in the absorber. A pump, pumps the solution to a higher pressure. A gas-fired burner, or steam or waste heat, provides heat input to boil the solution causing the release of refrigerant vapour. The refrigerant vapour condenses releasing its heat to the heat sink and returns to the evaporator where the cycle is repeated.

Engine-driven cooling equipment consists, as the name suggests, of a gas engine-drive coupled to a conventional vapour compressor. The refrigeration equipment is identical to that used in electrically-driven air conditioners or chillers, with the exception of the drive. A refrigerant such as CFC, R12 or HCFC, R22 absorbs heat from the building in the evaporator, changing state from a liquid to a gas. The gas is compressed by the compressor to a higher pressure. The high-pressure refrigerant gas releases its heat, in the condenser, to the heat sink, changing back to a liquid. The liquid enters the evaporator and the cycle is repeated.

Desiccant-based cooling equipment is based on the physical process by which some gases, such as water vapour, are sorbed by liquid or solid desiccant materials. The water vapour that is sorbed is subsequently evaporated and thereby provides cooling effect. The desiccant is regenerated or dried by heat from a gas-burner, or an exhaust air stream and the cycle is repeated.

2.2 RELATIVE ADVANTAGES AND DISADVANTAGES

Absorption cooling equipment uses non-CFC working fluids, therefore it does not contribute to atmospheric ozone depletion. Since it uses a clean burning fuel as the energy input, such as natural gas, the environmental impact is lessened compared to power plants using coal or oil to produce electricity. Absorption equipment can be highly reliable and the absence of mechanical compression can lead to a reduction in maintenance costs.

One significant disadvantage is the relatively low coefficient of performance (COP) of absorption equipment relative to electric alternatives. Improvements, such as the development of double-effect cycles, have reduced this disadvantage.

Engine-driven equipment can use readily available refrigeration compressors and other components common in many ways to the electrically-driven cooling equipment, thus minimizing cost. In engine-driven cooling equipment the refrigerant does not contact the drive as it would in the more common hermetic electrically-driven compressors. For this reason, engine-driven equipment will be more readily adapted to the new non-CFC refrigerants.

Engine-driven equipment does require more maintenance and service than absorption equipment because of its greater number of moving parts, but highly developed engines may minimize this.

Desiccant-based cooling equipment offers a number of marketable advantages compared to other gas cooling technologies. Combining desiccant dehumidification (latent cooling) with conventional electric cooling can reduce the electrical demand associated with cooling and can result in reduced duct sizes and coil sizes, as only sensible cooling is provided by conventional cooling systems. Improved indoor air quality due to absorption of various moist contaminants, less maintenance and long life are other benefits of desiccant cooling systems. Desiccant-based cooling equipment is best suited to applications with high latent to sensible load ratios, or for reducing the need for electrical upgrade at the time of building additions.

Significant disadvantages are a relatively high cost, the need to combine with another type of gas cooling or electric cooling equipment to be able to provide sensible cooling and a relatively low COP compared to double-effect absorption or engine-driven equipment.

2.3 GAS COOLING EQUIPMENT PERFORMANCE

The performance of cooling equipment and heat pumps can be described in a variety of measures and units. The Coefficient of Performance (COP) is a common measure. Another is the Seasonal Performance Factor, or more recently the Seasonal Energy Efficiency Ratio. COP is defined as useful power output divided by electrical or other supplied input and is reported under a specific set of standard test conditions. The seasonal values involve units of energy output divided by energy input and span the entire season. The seasonal values depend on local climate, equipment sizing in relation to load and part-load performance of the equipment, while the COP values do not.

This study reports on COPs. The seasonal performance factors for the same machines would have the same ranking as the COPs. Seasonal performance factors can often be higher, because COP ratings are normally taken at extreme conditions.

The following values of cooling COP are at standard rating conditions for equipment of that type.

Absorption equipment cooling COPs range from a low of about .5 or .7 for single stage or single-effect to a predicted high of about 1.5 for three stage or triple-effect. Absorption heat pump equipment has heating COPs from a low of 1.25 for single-effect equipment to a high of 1.8 for double-effect.

Engine-driven equipment cooling COPs are higher than single-effect absorption cycles and range from about .8 to 1.4 depending on the size of the equipment. Engine-driven heat pump COPs are reported in a range from 1.4 to 1.9.

Desiccant-based cooling equipment COPs are lower than current day absorption or engine-driven equipment with values in the range of .5 to .8, with the latter typical of two-stage desiccant wheel systems.

Competing electric cooling equipment standard rating efficiencies, at the same test conditions, are provided here for comparison:

- central electric air conditioner, COP = 3.0;
- packaged roof-top air conditioner, COP = 2.5;
- reciprocating compressor chiller, COP = 4.0;
- centrifugal compressor chiller, COP = 5.0.

If the inefficiencies of power generation, particularly when fossil fuels are used, transmission from source to end use, and the efficiency of the cooling equipment are taken into account, the differences between the above gas cooling COPs and electric cooling COPs become much smaller.

2.4 GAS COOLING EQUIPMENT AVAILABILITY/DEVELOPMENT STATUS

During the investigation, contact was established with 18 existing manufacturers or their representatives to obtain information on the available gas cooling equipment.

Absorption equipment is available from a number of manufacturers for residential, commercial and industrial cooling applications. Available equipment ranges in capacity from 3 to 1100 tons. The residential products are available from the Dometic Corporation, while Trane, York and Carrier offer Japanese produced chillers for the commercial market. York anticipates manufacturing the Hitachi double-effect absorption units in North America at a substantial reduction in cost. The residential equipment, available at this time, is single-effect only. The commercial products are all double-effect, lithium-bromide-water.

The **engine-driven cooling equipment** market has a number of products. Tecogen Inc. offer a range of centrifugal and screw-equipped compressor chillers for the commercial market. Thermo-King, well known in the trucking refrigeration industry, have a 15 ton packaged roof-top air conditioner driven by a Hercules engine, with a 25 ton model soon to be introduced. Trane Company have 55 ton and 80 ton chillers driven by Hercules engines in their product line. Yamaha, Aisin Seiki, and Sanyo have engine-driven air conditioners (heat pumps) under development.

There were only two **desiccant-based cooling** products identified in the study. Munters Cargocaire offer a desiccant-based packaged roof-top unit intended for supermarket or small/medium commercial applications. Water removal capacities between 55 and 110 kg/hr are available. ICC Technologies offer a similar product but with water removal rates up to 225 kg/hr. Both employ silica gel and/or lithium chloride as the desiccant.

Many very promising new gas cooling equipment developments are nearing commercialization, including Yamaha, Aisin Seiki, Sanyo, and York. The York International/Briggs and Stratton Corporation, 3-ton residential engine-driven heat pump promises a seasonal COP in heating of 1.7 and in cooling of .9 which is better than currently available equipment. Other developments to watch are the high efficiency, triple-effect chiller by the Trane Company and the Battelle double-effect absorption air conditioner. Both are still at the relatively early stages of development. All of these developments are being undertaken with funding support from the Gas Research Institute.

3. PERFORMANCE AND ECONOMICS COMPARED TO ELECTRIC COOLING

The performance and economic attractiveness of competing systems was estimated through computer simulations. A large office building, a medium office building and a single family residence were matched up to appropriate gas-fired and electric cooling equipment to determine their relative performance and economics.

The buildings were assumed to be located in the Toronto area and both the City of Toronto and City of North York electricity and gas rates were employed to estimate operating costs.

The competing cooling systems were as follows:

• Large office	- centrifugal electric chiller - double-effect absorption chiller
• Medium office	- reciprocating electric chiller - engine-driven chiller
• Residence	- air-source electric heat pump - engine-driven heat pump

For the two commercial buildings, computer simulations of system performance were undertaken using the United States Department of Energy developed DOE 2.1D computer program. The residential simulations were undertaken with a bin method energy analysis. Figures 1, 2 and 3 present the more promising results of the performance comparisons. The impact of incentives is also shown.

Based on City of Toronto electricity and gas rates, the double-effect absorption chiller in the **large office building** cooling plant showed a simple payback period of about 7 years. When the cooling load in this building was shared between a double-effect absorption chiller and an electric chiller, the simple payback period was almost cut in half to 3.7 years. If Ontario Hydro's "Savings by Design" demand-management incentive was available to either system the payback periods would drop to 3.5 and 1.8 years respectively.

The **medium office building** payback periods were longer, requiring the application of the demand-management incentives to reduce the payback period below 5 years. The engine-driven chiller with engine heat recovery was marginally more attractive than the chiller without engine heat recovery.

The **residential** engine-driven heat pump showed an annual operating cost reduction of $225 compared to its nearest electric competitor, an add-on electric heat pump to a conventional gas furnace. Assuming an incremental capital cost for the gas-engine unit of $1000 above the electric heat pump, the simple payback period is under 5 years.

None of the comparisons examined the maintenance cost differences between the gas and electric cooling equipment; there is simply too little information in this area to permit a meaningful estimate. Absorption equipment, however, is expected to have lower maintenance costs than competing electric technology due to the presence of fewer moving parts.

At the present time, it has not been determined whether gas-fired cooling equipment would qualify for "Savings by Design" demand-management, capital cost incentives. The summer peak demand reductions were approximately 25% and 20% in the large and medium size office buildings, respectively. Actual peak demand reductions were 700 kW and 60 kW, in the two buildings. These demand reductions are more than sufficient to qualify the buildings for "Savings by Design" incentives which provide grants for 50% of the incremental capital cost.

The performance and economic attractiveness of desiccant-based cooling systems was not evaluated in this study. Gershon Meckler Associates of the United States, however, have designed desiccant-based HVAC systems for different types and sizes of commercial buildings.

The systems generally combine a desiccant ventilation air dehumidification unit with an engine-driven chiller, in large buildings, or in smaller buildings with an evaporative air washer. Meckler's studies, in the large buildings, have shown that 20% additional peak demand cost reductions are possible compared to cold air, variable air volume, partial ice storage systems. Energy cost reductions of 20% are predicted as well. In the smaller buildings, total operating cost reductions of 40% are claimed. In both cases, the capital costs are significantly higher than the conventional systems, necessitating a gas or electric utility grant to improve the economics. For example, a capital grant of $13.50 per square metre would be required to eliminate the incremental capital cost difference in the large building described above.

4. ENVIRONMENTAL IMPACT OF GAS COOLING

The last phase of the investigation involved establishing estimates of the greenhouse gas effect of refrigerant and methane leakage rates, and engine, burner, and power plant emissions to calculate the relative impact of the competing commercial building systems on ozone depletion and global warming.

Refrigerant leakage rates were assumed to be the same for both engine-driven and electric chillers. The double-effect absorption chiller has no CFC's, so the ozone depletion potential is zero. The lithium-bromide and water mixture, used as the working fluid, is not a greenhouse gas.

The electrical generation mix in a particular locale will determine the amount of greenhouse gas emissions to be considered. In this study, the Toronto area, with the largest cooling market in Canada, is of primary interest. Ontario Hydro predict that 15% of the electrical energy in Ontario for 1993 will be produced by fossil-fuel-fired plants. The fraction at times of peak generation is of course considerably higher. In the provinces of Prince Edward Island, Alberta, Saskatchewan, Nova Scotia and New Brunswick the fossil-fuel generation exceeds 50%.

The equivalent mass of CO_2 gas emitted was calculated for each competing commercial cooling system referred to in Section 3. The effect of electrical generation, transmission, end use and refrigerant loss was accounted for in the case of electrical cooling systems. The effect of natural gas production, transmission, distribution, end use combustion and refrigerant loss, where appropriate, was accounted for in each gas-fired cooling system.

Figures 4 and 5 present the results for the large and medium office buildings. Here the annual equivalent mass of CO_2 emitted by the more promising gas-fired systems and the competing electric cooling plant are presented. One can see from the two figures that for the case of only 15% fossil-fuel generation, the annual equivalent mass of CO_2 emitted by the electric cooling plants is the lowest in the medium building. In the large office building, the double-effect absorption chiller has the lowest greenhouse gas emissions.

The large office building, Figure 6, shows a dramatic difference in the equivalent mass of CFC-11 emitted between the competing systems. The double-effect absorption chiller has no impact on the ozone layer, as stated earlier. The electric centrifugal chiller has the highest CFC-11 emission of 145 kg per annum. The combination electric-gas-fired chiller plant emits half this amount, or 72 kg per annum.

5. CONCLUSIONS

Gas-fired cooling equipment is most attractive in large office buildings, characterized as having annual cooling requirements in excess of annual heating requirements. The electrical building demand is due primarily to cooling operation and in locales where the electricity to gas price ratio is high. Combination gas/electric plants can exhibit more favourable payback periods than entirely gas-fired cooling plants due to the lower capital costs and the fact that the majority of cooling loads can be met with the cooling system operating at less than design cooling capacity.

The application potential of all gas-fired commercial building cooling equipment would be significantly enhanced if electrical demand reduction incentives were available for dual-fuel or fuel substitution applications. Gas-fired cooling offers significant load-levelling benefits to summer peaking electric utilities and winter peaking gas utilities. A portion of the avoided cost of new generation capacity could be used to encourage gas-fired cooling in such locales as the City of Toronto where this situation exists.

Desiccant-based gas-fired cooling equipment can be combined with electric cooling equipment to permit smaller electric-driven compressors and lower electrical demand. Relatively high capital costs have limited widespread application necessitating the application of utility grants to foster applications in small and large commercial buildings.

Gas-fired cooling equipment can be environmentally attractive, compared to competing electric systems, in terms of reduced ozone depletion and lower overall greenhouse gas emissions. The absorption chiller, examined in the large office building, reduced CO_2-equivalent emissions by 20 percent compared to the electric chiller and eliminated CFC-11 emissions altogether. The greenhouse gas reduction would be even greater in regions where a higher percentage of the electricity is produced by fossil-fuel-fired generation. In other cases, however, where both systems use refrigerant the electric cooling systems can have lower CO_2 emissions. This was the case in the medium office building presented in Figure 4.

Currently the most promising gas-fired cooling available is double-effect absorption with products from Yazaki, Hitachi, and Sanyo available. The York International, Briggs and Stratton and GRI, three ton residential engine-driven heat pump, the Tecogen/Carrier and Trane/Hercules commercial engine-driven centrifugal chiller and the Trane commercial building triple-effect absorption chiller offer potential for the future.

6. RECOMMENDATIONS

Gas/electric combination cooling systems were found to be attractive commercial building applications. The degree of attractiveness is a function of the relative price of electricity and gas and the efficiencies of the gas and electric equipment. Only plants with equal electric and gas-fired cooling capacity where examined. Other cooling capacity splits should be investigated, as should other gas/electric cooling equipment combinations to determine the optimum for different fuel prices and efficiencies, with and without utility incentives.

Buildings other than office buildings in the commercial/institutional sector may offer more attractive opportunities for all-gas or combination gas/electric cooling plants. Buildings with electric peaks due to electric cooling, such as large retail, restaurants and fast-food outlets should be investigated as prospects for gas-fired or combination cooling equipment.

Other gas-fired systems remain to be evaluated under Canadian conditions. The desiccant dehumidification and combination desiccant/electric cooling systems, proposed by Meckler, may be competitive in Canada in certain commercial applications. Another promising system would be a combination desiccant dehumidifier/evaporative cooler which could eliminate the need for vapour compression cooling systems in residences and their associated CFCs and HCFCs.

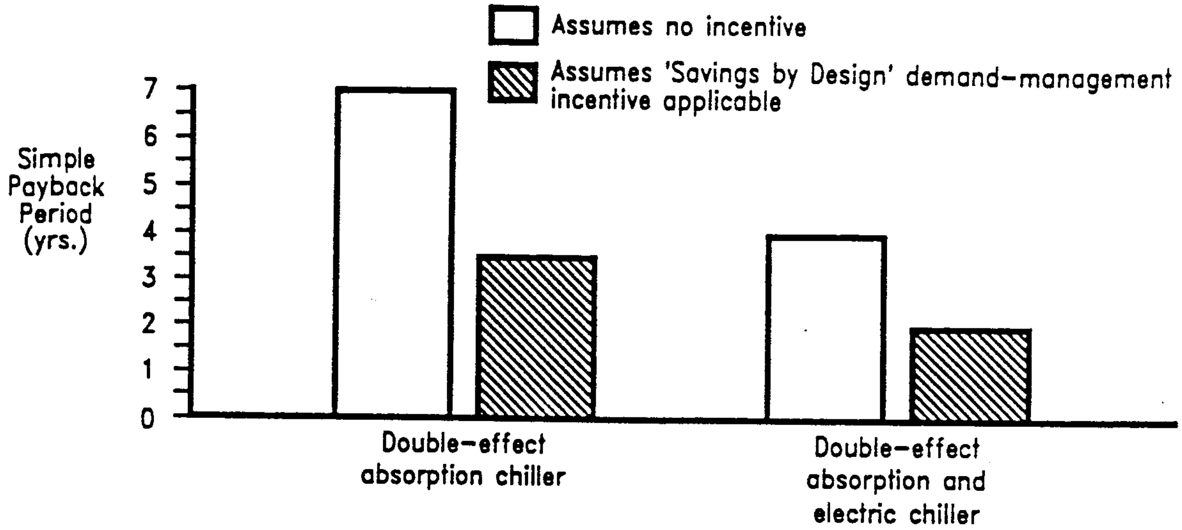

Figure 1 Economic Attractiveness of Gas-Cooling – Large Office Building – City of Toronto

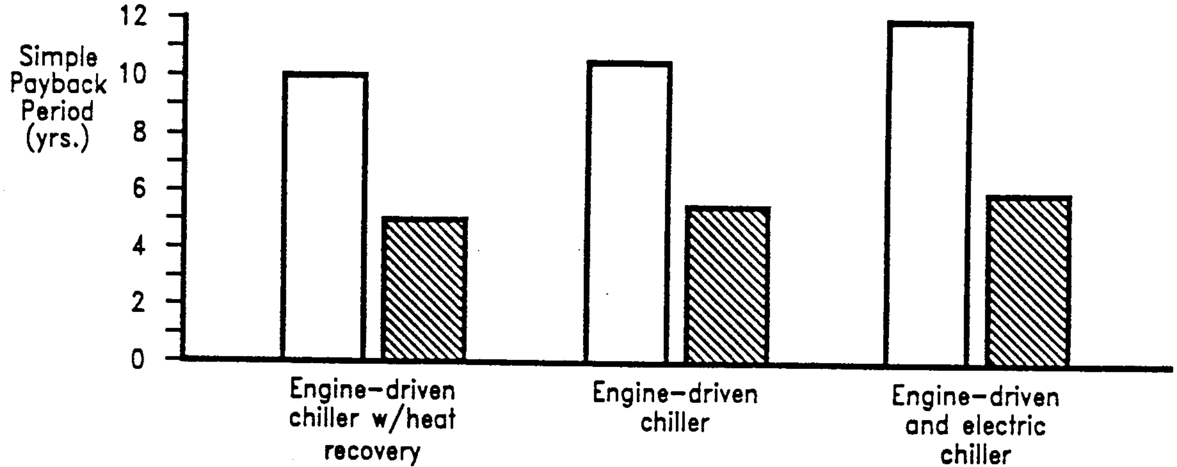

Figure 2 Economic Attractiveness of Gas-Cooling – Medium Office Building – City of Toronto

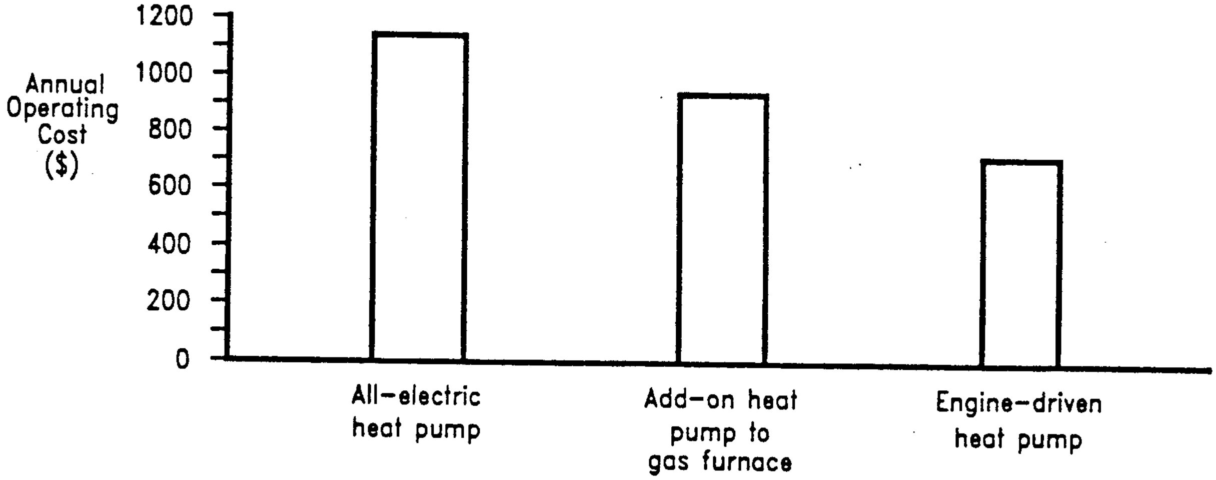

Figure 3 Economic Attractiveness of Engine-Driven Heat Pump – Single Family Residence – City of Toronto

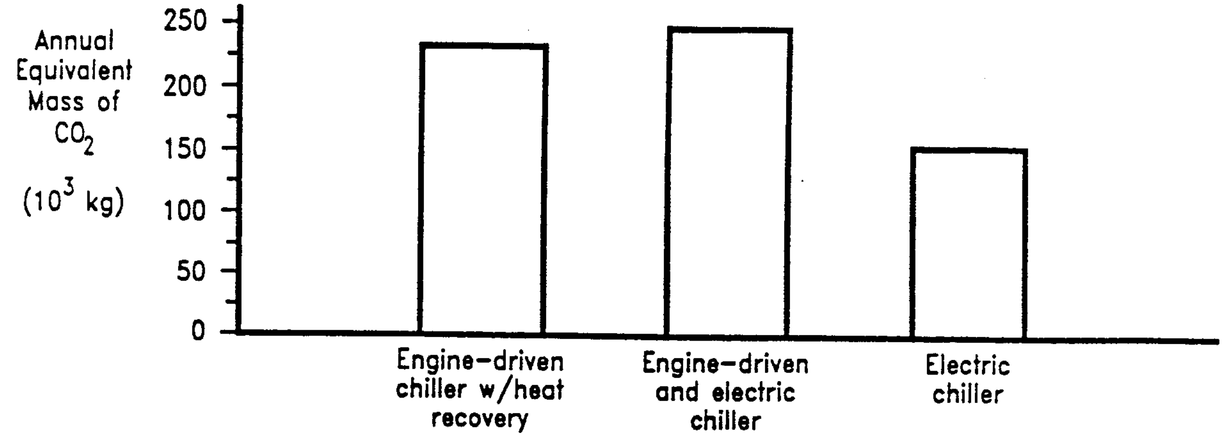

Figure 4 Equivalent CO_2 Produced in Medium Office Building - City of Toronto

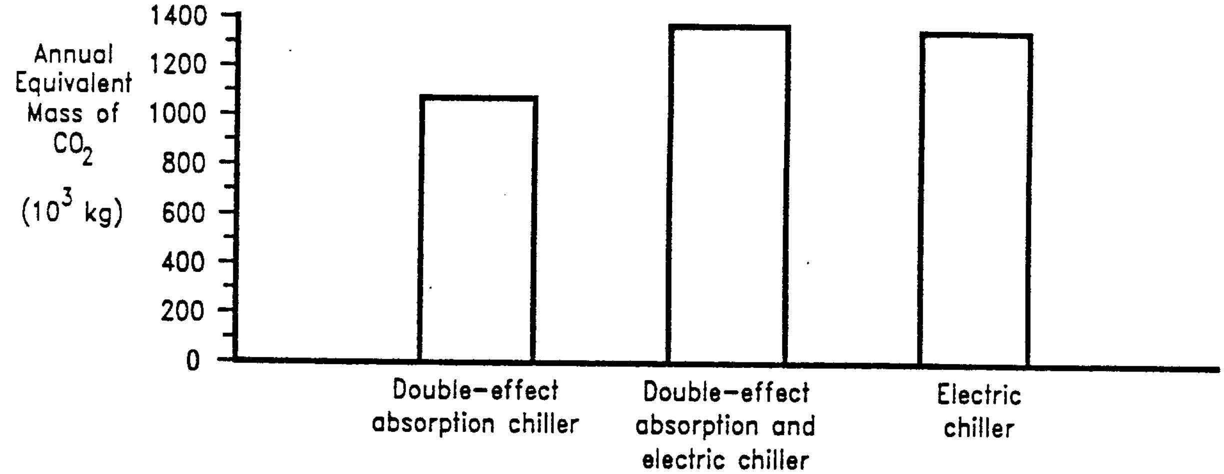

Figure 5 Equivalent CO_2 Produced in Large Office Building - City of Toronto

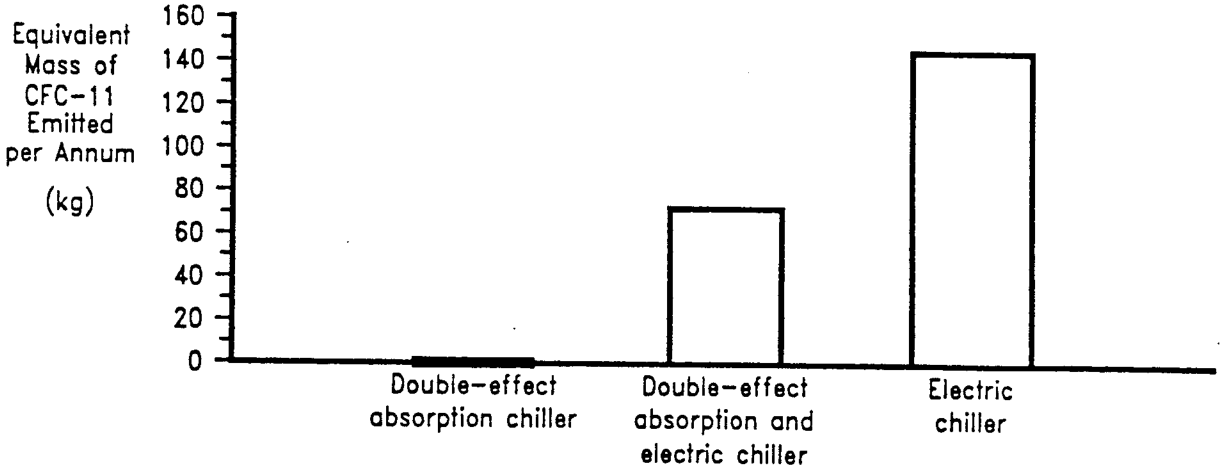

Figure 6 CFC-11 Emissions - Large Office Building - City of Toronto

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Fax: (718) 797-4705

Gemini Energy Systems Inc.
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Corpus Christi, Texas
U.S.A. 78469
Fax: (214) 753-0629

Cargocaire Engineering Corp.
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Servel Gas Air Conditioning
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Yamaha Motor Corp. (Canada) Ltd.
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Bry-Air Inc.
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Route 37 West
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U.S.A. 43074
Fax: (614) 965-5470

DRYOMATIC, Division of Airflow Co.
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Fax : (301) 695-4057

Kathabar Systems
Division of Somerset Technologies Inc.
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Fax: (201) 356-0643

Niagara Blower Company
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Buffalo, New York
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Fax: (716) 875-1077

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Ebara International Corp.
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U.S.A. 95682

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Semco Manufacturing Inc.
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U.S.A. 65205
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APPENDIX A

STATE-OF-THE-ART OF GAS-FIRED COOLING TECHNOLOGY DEVELOPMENT

The five appendices in this document constitute the interim reports prepared by Caneta for Consumers' Gas and Energy, Mines and Resources Canada during the progress of the gas cooling study.

The appendices are:

- Appendix A: State-of-the-Art of Gas-Fired Cooling Technology Development - a detailed review and analysis of published results of gas-fired cooling developments, including a complete literature reference list;
- Appendix B: Update on Gas-Fired Cooling Technology Developments - results of direct contact with the technology developers/sponsoring organizations of developments previously identified;
- Appendix C: Performance and Economic Attractiveness of Gas Cooling Compared to Electric Cooling in Canadian Buildings - results of computer simulations used to assess attractiveness of gas cooling versus electric cooling in commercial and residential buildings located in the city of Toronto;
- Appendix D: Environmental Impact of Gas Cooling Technologies -gas cooling and electric cooling equipment are compared with respect to their relative impact on ozone depletion and global warming potential;
- Appendix E: Commercially Available Gas-Fired Cooling Equipment -a summary of performance and feature information on gas cooling products currently on the market.

STATE-OF THE-ART OF GAS-FIRED COOLING TECHNOLOGY DEVELOPMENT

1. INTRODUCTION

The first phase of this investigation of gas-fired cooling involved a detailed review and analysis of published results of technology developments. These developments were identified: in research report directories published by the Gas Research Institute; articles published in the International Energy Agency, Heat Pump Centre Newsletter; in the 3rd I.E.A. Heat Pump Technology Conference Proceedings, from a meeting held in Tokyo in March 1990 and in proceedings of the 1st and 2nd Department of Energy, Oak Ridge National Laboratory Conferences, on Research and Development on Heat Pumps for Space Conditioning Applications held in 1984 and 1988 respectively.

A total of about 225 titles were identified in the initial search of the directories, newsletter and, proceedings cited above. To keep the review within the level of effort originally intended for this phase of the investigation, only the major North American technology developments were targeted for in-depth analysis.

These North American developments with few exceptions, were sponsored by either the Gas Research Institute (GRI) or the Department of Energy (DOE) or both of these organizations. The scope of the technology development review was thereby reduced to about 85 publications or technical articles on the major North American gas-fired heat pump or cooling developments.

In addition to a review and analysis of the major technology developments, this phase of the program also permitted an evaluation of the available information for later phases of the program. For example:

- equipment performance specifications for the computer simulation of gas-fired cooling technology in representative Canadian cities;
- information which would permit an assessment of the environmental benefits of gas-fired versus electric cooling equipment. This information could be greenhouse gas production coefficients for different fuels as a function of end-use gas and electricity consumption. Approaches to determining the environmental benefits would also be of interest;
- whether any of the gas-fired technologies has been assessed with respect to their electrical demand management potential. Ontario, where the electric utility is incenting electrical demand reductions at the design stage and at time of retrofit, niche

opportunities may exist for gas-fired cooling technology, in both residential and commercial applications.

The following sections will describe: how the different gas-fired cooling technologies work; the residential and commercial heat pump cooling equipment development undertaken or currently underway; the problems encountered, solutions to the problems, the performance expected or measured, and the reported status of the various developments.

2. ABSORPTION EQUIPMENT

Absorption cycles have been used for over fifty years in refrigeration applications, traditionally using either ammonia-water, or water-lithium bromide as the refrigerant-absorbent pair. Gas-fired absorption air conditioners were introduced in the late 1950's and were a significant consumer product until the mid-1970's when changing fuel prices and reliability problems almost eliminated them from the market.

In the late 1970's, efforts were made to develop single-effect absorption heat pumps. Although absorption technology could yield a heat pump with a coefficient of performance (COP) in heating greater than that achieved by a gas furnace or boiler, it could not bring the COP in cooling over a threshold of unity. Since this performance level was not adequate enough to make these machines competitive, research was concentrated on improving new types of absorption cycles. The coefficient of performance (COP) or efficiency of gas-fired cooling equipment is defined as the cooling or heating capacity divided by the gas input expressed in the same units. The electric input for fans or pumps often is not included, as would normally be the case for electric air conditioning equipment.

Research on double-effect and advanced absorption equipment has been funded by GRI and DOE since the early 1980's. These systems have higher efficiencies than previous absorption cycles, and involve heat exchange between absorbers and generators, or between two individual cycles thermally linked together.

For chillers, however, the cooling performance of even the best double-effect cycles cannot compete with high efficiency electric chillers. Therefore, DOE initiated a program to increase the cooling performance of absorption technology. This program led to the concept of a triple effect chiller by Oak Ridge National Laboratory (ORNL). This cycle is calculated to have a 20% to 60% higher efficiency than an equivalent sized double-effect cycle.

The following subsections describe research and development efforts performed in North America on absorption equipment in the past fifteen years.

2.1 RESIDENTIAL/SMALL COMMERCIAL

DOE and GRI have sponsored or co-sponsored seven developments in residential/small commercial absorption equipment. Six of these developments have involved heat pumps, while the other involved an absorption chiller for solar cooling. Three of the developments were initiated in the late 1970's involving single-effect cycles of which two have been discontinued; it is expected that the same is true for the third. Single-effect cycles do not have the performance levels to be competitive versus other technologies. The other four projects, involving either double-effect or advanced cycles, are reportedly at the field testing phase.

In 1979, with DOE support, **Arkla Industries Incorporated** (2.1, 2.2) initiated a project to develop a heating-only, ammonia-water, single-effect absorption heat pump. The non-reversing approach simplified design while improving reliability and coefficient of performance. By 1983, a prototype had been tested yielding a steady-state COP in heating of 1.25 with a capacity of 63,000 Btu/h. Had the heat pump been made reversible it would have had a cooling capacity of two tons. Due to a predicted selling price in 1981 of $4,000, development was stopped and the heat pump never reached production.

At about the same time, Arkla Industries was also developing a direct evaporatively-cooled three ton absorption chiller, using lithium bromide/water absorption technology, as a means of heat rejection for solar cooling equipment. The unit consisted of concentric drums with spaces between them. The inner drum contained the generator with the annulus surrounding it acting as a condenser; the outer annuli comprised the absorber. A unit was built with a COP in cooling of 0.72 and field tested in 1979. Additional research efforts have not been reported.

With support from GRI and DOE, **Allied Corporation** (2.3, 2.4) developed a single-effect absorption heat pump using R-123 a (triflurochloroethane) as the refrigerant and ETFE (ethyltetrahydrofurfurylether) as the absorber. Prototype heat pumps were tested and showed a heating COP of 1.25 and a cooling COP of 0.50. From these tests it was predicted, with further development, that the heating COP could be increased to 1.50, making the heat pump more competitive with other technologies. Development work was performed on the key components of the system: the generator, condenser, absorber, evaporator, solution pump and flow and safety controls.

A detailed economic analysis was undertaken which compared the study's "present day (i.e.1985) technology level" versus two alternative competitive systems: an electric heat pump, and a high efficiency gas furnace, coupled with an electric air conditioner. As well, comparisons were made of the predicted technology five years in the future (i.e. 1990). In a survey of seven cities in the United States, the absorption heat pump was found competitive or superior to the electric heat pump in four cities, for 1985 technology, and five cities, for 1990 technology. The absorption heat pump was competitive or superior to the gas furnace/electric air conditioner in two cities for 1985 and six cities for 1990 technology. Although this analysis showed encouraging results for the absorption heat pump, the system was never further developed or manufactured as it was concluded that the single-effect performance levels were not sufficient to offer reasonable economic incentive for customer acceptance.

In the mid-1970's, **Columbia Gas System Service Corporation** (2.5, 2.6, 2.7), later co-funded by GRI for the period of 1980-1985, started development of a double-effect absorption heat pump using ammonia as the refrigerant and sodium thiocyanate (NaSCN) as the absorbent. For a production unit, the target COP's were 1.50 in heating and 0.8 in cooling even though testing of a prototype attained higher values (1.65 and 0.82, respectively). In this unit, state-of-the art components and controls were heavily emphasized. Critical problems that were solved consisted of corrosion, solution pump design, energy recovery, system weight/cost and heat exchanger optimization.

An economic analysis showed that the absorption heat pump could reduce the cost of heating of an average residence by 33%, as compared to a high efficiency condensing gas furnace, and by 50%, as compared to a standard gas furnace. The absorption heat pump provided space cooling at twice the efficiency of gas air conditioners. The system has been developed to the point where manufacturer commitment to the program is now essential to ensure commercialization.

In 1982, DOE sponsored **Phillips Engineering Company** (2.8, 2.9) in their development of an advanced absorption heat pump which incorporated generator/absorber heat exchange (GAX). Benefits of GAX technology is simplicity of design and minimum total heat exchange as compared to other cycles with equivalent efficiency. In a GAX cycle, heat exchange requires significant overlap of solution temperatures at the high temperature end of the absorber and at the low temperature end of the generator. This yields similar results to the double-effect cycle in which the first stage absorber supplies heat to the second stage generator, yet now the process is accomplished without the complexity of double effect.

The system, which uses an ammonia-water solution, has achieved the target COP's of 1.8 in heating and 0.9 in cooling. Major problems in the development were assuring that all available heat is recuperated into the cycle, and the development of reliable absorption solution pumps and flow control valves. Phillips had plans for a multiple unit field test to be initiated in 1990.

In mid-1983, GRI funded **Battelle Columbus Division** (2.10, 2.11) to develop a dual-cycle advanced absorption heat pump. The dual-cycle concept thermally links two conventional single-effect absorption cycles, yielding a high performance system, without high pressures or the need for new unproven working fluids. Project goals were to develop a three ton unit with a heating COP of 1.80 and a cooling COP of 0.94.

Linking the two cycles is the "absorption power module" (APM). The APM combines many functions into one modular unit: it provides primary heat input to the heat pump system from the burner, it provides for heat transfer from one loop to the other, it contains the desorbers for both individual heat pumps and the H_2O condenser. The Battelle heat pump system uses lithium bromide-water in the high temperature subsystem, where water is the refrigerant, and ammonia-water in the lower temperature subsystem, where ammonia is the refrigerant. As operating temperatures are above freezing in the high temperature subsystem water can be employed as the refrigerant. The lithium bromide system buffers the ammonia system from the high pressures while the ammonia system buffers the salt solution from crystallization, allowing the salt to operate at higher pressures. The initiation of field testing was scheduled for mid-1990.

GRI has also funded Battelle in development of a double-effect air conditioner-heater which uses water and lithium-bromide. The project planned for a cooling COP of 1.0 while delivering 36000 Btu/h, and a heating COP of 0.85 while delivering 27000 Btu/h. The system would use a direct air-cooling evaporator to eliminate the chilled water-loop, pump and coil. Targeted for the Southern United States market, field testing is scheduled for 1992 with market introduction for 1993.

2.2 COMMERCIAL

Four projects have examined developments of absorption equipment for commercial applications. Two of these projects, sponsored by GRI, examined advanced absorption cycles, but the research was stopped because the market potential was not strong enough. The other two projects are licensed applications of the patented Oak Ridge National Laboratory triple-effect cycle. Research has just begun on these two projects so information has not yet been published.

In 1982, the **Carrier Corporation** (2.12, 2.13), with sponsorship from DOE, developed a dual-loop heat pump using ammonia-water in the lower temperature loop, and lithium bromide-water in the upper temperature loop. The upper loop evaporator received heat from the lower loop condenser and/or absorber, while the upper loop condenser and absorber operated at higher temperatures than the lower loop's generator. Based upon lab testing, the predicted performances were a COP in heating of 1.76 and a COP in cooling of 1.02.

An economic analysis showed that the installed cost of this system would be 20% higher than conventional equipment, resulting in payback periods of between 5.5 and 7.5 years. In northern climates which have 4000 or more hours of heating/cooling per year, with the heating load being about 70%-80% of this total, and with electric demand charges of $100/kW/year or higher, the system had a payback period of about three years. Nevertheless, the evaluation did not show good market potential and the project was discontinued.

DOE also sponsored the **Trane Company** (2.14, 2.15, 2.16) in their development of a generator-absorber heat exchange (GAX) cycle. From lab tests, the cycle had predicted COP's of 1.61 and 0.8 for heating and cooling, respectively. During development, problems arose in the low performance of the absorber/generator heat exchange, with rectifier flooding, with system control and corrosion of the boiler. In a computer simulation, a 150 ton GAX absorption heat pump applied to an apartment building in Chicago was predicted to have a payback period versus electric air conditioning and gas boiler of 2.2 years. Though the economics showed promise in northern climates, the overall economics did not support commercialization in the United States. In 1988, Trane discontinued support of the GAX absorption heat pump deciding instead to support a triple-effect chiller development.

In 1988, Trane licensed the triple-effect chiller design originating at Oak Ridge National Laboratory and, with GRI sponsorship, started developing a chiller for large commercial applications. The project goal was to achieve a cooling COP of 1.5. Trane is planning a proof of concept demonstration for the 150 ton and larger units by 1991.

In 1989, **Apache** (2.17), an independent oil and gas production company, also licensed the Oak Ridge triple-effect chiller for use in cogeneration applications of 150 tons and less. Since development of the system by Apache only started in late 1989, information has not been published.

3. ENGINE-DRIVEN EQUIPMENT

The adaptability of an engine rather than electric motor drive to the traditional vapour compression refrigeration cycle shows promise for gas-fired cooling and heat pump applications, both in residential and commercial buildings. The inherent variable-speed capability of some engines may offer part-load efficiency advantages compared to single speed electric motor drives. Compressors operating at lower speeds, characteristic of variable-speed engine drives, last longer than compressors driven by electric motors at speeds of 1800 rpm or higher. With heat recovery from both engine exhaust and jacket cooling water COPs or efficiencies are also potentially higher than other gas-fired cooling or heat pump configurations. Engine-driven cooling equipment has COPs between .77 and 1.4 depending on size and whether or not heat recovery from engine exhaust or cooling water is done.

However, there are many potential drawbacks which have required research and development. Traditional automotive-derivative engines have limited life and require complete overhaul at relatively short intervals and frequent maintenance. Automotive engine life is typically 1,000 to 3,000 full-load operating hours. While industrial engines are capable of 30,000 hours of full-load operation between overhauls, they are five times more costly on a brake horsepower basis. Another area which has seen considerable development attention is the shaft seal that prevents refrigerant leakage in the typical open-drive engine configuration.

Beyond the traditional industrial or automotive-derived engine drives, other engine concepts promising simplicity of design, improved reliability and efficiency have been examined. These other drives have included kinematic or mechanically-driven and free-piston Stirling engines. The free-piston Stirling engine drives have been both hydraulically and magnetically-coupled to a vapour compressor. The kinematic development employed an open drive to a reciprocating compressor. Other than the Stirling engine, the Braun linear internal combustion engine has been investigated for commercial gas-fired rooftop heat pump application.

The following subsections describe engine-driven equipment developments undertaken over the last decade.

3.1 RESIDENTIAL

The DOE and GRI have sponsored or co-sponsored three gas-fired engine driven heat pump developments intended ultimately for the residential cooling market. Two of these developments have involved a Stirling engine, chosen for its high thermal efficiency, multi-fuel capability and quiet operation (3.1). The free-piston type Stirling engine was chosen, in both cases, because of its potential long life, reliability in heat pump application and compatibility with hermetic heat pump compressor design.

Mechanical Technology Incorporated (MTI) (3.2,3.3) proposed the development of a freepiston Stirling engine (FPSE) hydraulically-coupled to a vapour compressor. The deflection of an engine diaphragm, by helium pressure, transfers the engine power to the compressor through a hydraulic transmission. The presence of the diaphragm separates the engine working fluid, helium, from both the hydraulic transmission fluid and the compressor refrigerant. The hydraulic transmission and diaphragm eliminate the need for a drive shaft and associated seal leakage. A linear motor displacer control was employed to control the engine over the wide range of loads encountered in heat pump operation. The displacer achieved capacity variation by varying displacement stroke.

During 1987 (3.4) this Stirling engine heat pump was tested at Lennox Industries Engineering facility in Dallas, Texas. Performance was evaluated over the temperature range from 0 °F to 95 °F for a range of evaporator and condenser test conditions and compressor piston displacement strokes. An engine peak efficiency of 25 percent was recorded. A cooling capacity of just over 3 tons was measured at standard rating conditions (95 °F) with a corresponding COP of .91. Heating capacities of 60,000 Btu/hour at 47 °F and 35,000 at 17 °F were also measured, with COPs of 1.61 and 1.04, respectively. Earlier problems due to compressor piston ring seal leakage and excessive transmission losses had been overcome in the breadboard prototype evaluated in Lennox Industries test facilities.

Sunpower Incorporated (3.5) were supported by the DOE and Oak Ridge National Laboratory in another FPSE development employing a magnetic coupling between the engine and compressor. Other methods of coupling investigated had proved to be too complex or had limited life. The magnetic coupling promised direct coupling with hermetic sealing between the helium working fluid in the engine and heat pump refrigerant. The significant drawback was the unavailability of extremely powerful magnets, at reasonable cost.

The magnetic coupling acted like a powerful spring between the engine piston and the compressor piston. Magnetic material was located on both the engine piston and the compressor piston. The two components were arranged such that they attracted each other through the pressure vessel separating the two working fluids.

Since the vapour compressor is subjected to varying pressures/temperatures over the operating range of the heat pump, an imbalance in forces may exist at different operating conditions away from design. It was found that for small engine power of say 3kW, the imbalance at off-design conditions was small. This may limit the magnetically-coupled Stirling engine to small residential heat pump systems. At last report, a design of a 3kW Stirling engine magnetic-coupled, heat pump system was to be undertaken before proceeding to system testing.

The MTI and Sunpower Stirling developments were said to be high risk/long term developments by both the Gas Research Institute and the Department of Energy. The adaptability to conventional heat pump cycles, limited number of moving parts and high engine efficiency were the main attractions to the Stirling cycle.

One additional engine-driven heat pump development supported by GRI is mentioned briefly in (3.6). Battelle Columbus was said to be developing a 3 ton engine-driven heat pump with target heating COP of 1.7 and cooling COP of 1.0, in collaboration with an HVAC manufacturer. This development was described by GRI as a relatively low risk approach, for a near to mid-term gas-fired heat pump product. No further reporting on this development could be identified.

3.2 COMMERCIAL

Four engine-driven heat pump or cooling systems intended for commercial building application are now commercially available or under development. While two are based on current engine technology, the other two involve the development of novel engine concepts. All four have received GRI funding at one time or another and linkages with HVAC equipment manufacturers have been established for the commercialization phase.

In 1987, **American Gas Association Laboratories** was awarded a contract to work with **Thermo King** to develop a 15 ton gas engine-driven rooftop cooling package (3.7). The refrigeration module has a Thermo King reciprocating compressor driven by a Hercules

NG-1600 gas engine. The same engine also drives the condenser and radiator fans. The engine can operate at three speeds with a full-load COP of .77. At outdoor temperatures below the full-load operating condition of 35 °C, the engine operates at lower speeds and a higher COP is possible. Since there are far more operating hours at temperatures below the full-load operating point, the seasonal COP can be as high as 1.0. A maintenance interval of 3000 hours is recommended. Thermo King are seeking utilities with an interest in evaluating these units in a field trial.

In 1985, GRI initiated a development with **Tecogen Inc.** to develop a 150 ton gas-fired engine-driven chiller for commercial buildings (3.8). Under standard rating conditions, a COP of 1.4 has been measured. A modified 454 cubic inch General Motors engine drives a Howden twin-screw compressor. The engine can vary operating speed and hence capacity, as required to enhance part-load performance. Field trials with seven units were conducted in 1987. Over 23,000 hours of operation were logged. Minor design changes were made and the units became commercially available in 1988. Over 100 orders had been received by the fall of 1989. While no details are known at this time, there are apparently other developments underway involving this chiller. One involves using condenser hot water to regenerate a desiccant material which can dehumidify a conditioned air stream, without the need with a higher evaporator temperature for low evaporator temperatures. The air conditioner can supply sensible cooling only and thereby reduce the compressor electrical energy requirements. The other development involves an engine chiller/ice storage system for commercial building application.

Tectonics Research, Inc. (3.9, 3.10, 3.11) have been involved in a unique engine-driven heat pump development since the early 1980's. The efforts have been co-funded by GRI and DOE. The initial goals of the Tectonics development included high thermal efficiency, long life (15 years) reasonable servicing requirements (once per year), with major overhauls every five years. The Braun internal combustion engine, developed by A.T. Braun, President and Technical Director of Tectonics Research, Inc., is a linear engine with features such as simplicity of construction, low manufacturing cost and dynamically-balanced operation. The engine had been used in industrial gas-fired applications before and the challenge was to develop the same for application to a 15 ton rooftop heat pump. In the Braun engine, piston motion is linear, back and forth in a straight line. No rotating cranks or rocking connecting rods are present. In addition, there are no valves, valve-train gear, flywheel or distributor. However, the engine does have a spark plug, battery and generator. Lubricant to the piston is by drops similar to that used in the rotary automotive engine. The engine only has two moving subassemblies. The piston and rod and the balancing counterweight. Once started the engine operates at a resonant speed depending on both load and pressures. The piston stroke varies with load conditions. By controlling bounce-space pressures and fuel quantity, stroke can be varied to respond to load change.

In the heat pump application a unique seal assembly, consisting of a metal bellows, a mechanism to limit bellows travel and a means of controlling the pressure, across the bellows, is used to prevent refrigerant leakage at the sliding rod connecting the engine and compressor pistons.

In addition to re-designing components for low cost and longevity, Braun had its HVAC collaborator, Mammoth (a Division of Nortek) test an engine in an air-to-air heat pump of roughly 15 tons cooling capacity. The laboratory results indicated COP's at standard rating conditions of 1.6 in heating, .9 in cooling. No electrical use is included in the calculated COP and the heating COP assumes 75% recovery of exhaust and cooling jacket heat.

At last report (3.10) (spring of 1988), laboratory testing of a unit with the improved engine-compressor seal was about to get underway. Field tests of one or more units was also in the planning stage.

Stirling Power Systems Corporation together with Borg Warner (later York International) became involved in the development of a 10 ton air-to-air heat pump matched to the output of a kinematic Stirling engine. A kinematic or mechanically-driven, rather than free-piston, Stirling engine has an open drive to a refrigeration compressor. The development, funded by GRI, began in the early 1980's and was last reported on in 1989 (3.12, 3.13, 3.14, 3.15).

Early phases were concerned with engine cost reductions, durability and performance and the optimization of power and efficiency. The V160 Stirling Engine was originally developed by the Swedish FFV Group over a 12 year period with funding of $30 million. An important attribute of this engine was said to be its superior reliability and durability compared to Otto and Diesel engines.

All moving parts are enclosed, with the pistons/piston rings operating dry. The pressurized working gas system is thus separated from the lubricating oil system. While the power to weight ratio is equal to a diesel engine of similar size, the manufacturing cost premium was 20% higher. One V160 engine had been extensively tested for a generator set application, for over 6000 hours, without major failure. Engine efficiency on natural gas was measured between 29-31% at peak load.

For the heat pump application, a compressor was required with high COP, capacity, reliability over a wide range of speeds and operating conditions. Limited compressors were available, suited to these requirements. Piston compressors were selected for development because of their reliability.

By 1986, Borg Warner sold York Air Conditioning and dropped out of the program. York decided to continue its involvement until completion of the environmental testing, before making a final decision. Efforts by Stirling Power were concentrated on engine improvements, such as: combustion chamber improvements; pressure/lubricant separation seal development and compressor selection/matching to the engine.

By 1989, Stirling Power (3.15) had made significant efforts to reduce the cost of the drive system. York was no longer involved in the development but an Italian manufacturer was to be supplied an engine/compressor module for incorporation into a final gas-fired product.

4. DESICCANT BASED-COOLING PROCESSES

Most cooling systems provide both sensible heat removal or temperature reduction and latent heat removal or dehumidification. In a desiccant-based cooling system, latent heat is removed from the air stream through absorption or adsorption of moisture by a solid or liquid desiccant or drying agent. The desiccant is regenerated or dried through the addition of heat and the moisture released is rejected to the exhaust airstream.

Desiccant dehumidification finds application today in some moisture sensitive manufacturing and storage applications where decreased product rejection rates yield a quick payback on the investment in equipment. Applications such as these that require depressed humidity levels, or for other reasons have large dehumidification fractions, are likely to be economically attractive with desiccant systems. Desiccant dehumidification in combination with electric air conditioning equipment has also found economic application in some commercial situations such as supermarkets.

Sensible cooling may be added to such systems by incorporating indirect evaporative cooling and/or a direct evaporative cooler (also known as a swamp cooler). By combining these techniques "total" gas-fired systems that essentially eliminate the need for electricity may be constructed.

Desiccant dehumidification may also be combined with vapour compression air conditioning to reduce the equipment capacity required. Electricity is displaced by natural gas thereby lowering electric energy and demand charges. Other benefits claimed for desiccant cooling include:

- lower installed equipment costs as a result of reduced duct and coil size requirements;
- less maintenance due to the long life of desiccants;
- improved indoor air quality due to the absorption of various moist contaminants; and
- reduced overall energy costs if gas is much cheaper than electricity.

Significant limitations of the technology, not the least of which is relatively high cost (4.1), have to-date prevented the widespread application of desiccant cooling systems. Research and development efforts are underway, (budget approximately $5.4 million in both 1987 and 1988)through GRI contracts, to improve the cost-effectiveness of desiccant technology for gas-cooling-equipment. System and component development work thrusts are supported by research in desiccant materials and computer modelling. The following subsections describe desiccant cooling developments occurring in the last decade.

4.1 EARLY EFFORTS

Early attempts to develop solid desiccant systems for dehumidification and cooling, such as the MEC unit developed by IGT and the SODAC system developed by AiResearch and Dunham-Bush, were characterized by low COP (0.6), high parasitic electrical power and large size (4.2). Improved desiccant wheel technology patented by Exxon in 1983 resulted in analytically predicted COP's in excess of 2.0 and a COP > 1.0 was demonstrated in testing. Dunham-Bush attempted to develop a cost-effective cooling system, in the 5 to 7.5 ton size range, using this solid desiccant dehumidification technology and evaporative cooling. As suitable desiccant wheel matrices were not produced, test results were disappointing and the project was concluded. IGT continue to pursue the development of a 25 ton unit felt to be more cost-effective than the earlier development.

4.2 RESIDENTIAL

GRI have recently sponsored three residential-scale desiccant cooling system developments (Table 3). A liquid-desiccant dehumidifier that integrates with a conventional vapour-compression air conditioner was developed by Tecogen Inc. and Kathabar Division of Somerset Technologies. An equivalent solid desiccant-based system was to be developed and tested by Arthur D. Little. A closed-cycle solid-desiccant heat pump system is under development by two project teams: the Zeopower Co. and Thermax Inc.

Tecogen and Kathabar have developed a system that operates as follows: indoor air is dried as it comes in direct contact with the liquid desiccant in a cross-flow heat exchanger. The heat released in this drying process is transferred through the heat exchanger plates to an evaporatively cooled outdoor airstream that flows through alternate passages of the heat exchanger. The desiccant is pumped to a gas-fired boiler where it releases steam while being regenerated.

Simulation of the integrated liquid desiccant dehumidifier identified the preferred configuration as one with a simple gas-fired boiler for regenerating the desiccant rather than including heat recovery from the conventional air conditioner. A one-ton stand alone dehumidifier was designed, built and tested in the laboratory. While this "breadboard" version had a COP of 0.49 improvements were suggested that should allow a COP of 0.57 to be achieved (4.3).

Three field experiment units were built and testing has been done on two of these. A seasonal COP of 0.58 was obtained in Gaithersburg, Maryland and 0.50 was measured in Atlanta, Georgia (4.4). The units operated reliably after several start-up problems were overcome. If the design capacity of the two units had been more closely matched to the latent load, longer on-times (more than 5 minutes) would have been experienced and higher COP's should result. Further laboratory development and testing of preproduction prototypes is planned for a subsequent phase of this development.

Zeopower Co. and **Thermax Inc.** are developing a closed-cycle solid desiccant heat pump concept. To date, only the Zeopower work (4.5) has been documented in an open literature report. Since solid Zeolite desiccants are difficult to move in airtight conditions and intermittent operation is considered impractical, the solid gas system is divided into two separate containers which are alternately heated and cooled. Significant thermal energy regeneration, from the adsorption to the desorption part of the cycle, is therefore possible.

Zeopower constructed and tested a breadboard prototype containing 90 lbs of zeolite desiccant. This system operated with a COP of 1.1, at ARI conditions, while the capacity was 2000 Btu/hr. Increasing the transfer fluid flow rate produced a capacity of 6000 Btu/hr with a COP of 0.55. Based on this evaluation, a modulating 3-ton laboratory prototype unit, using 500 lbs of zeolite, was then designed. It was projected to weigh about 800 lbs, cost $2000 (1986) to manufacture and achieve an ARI gas COP of 1.0 when operating at one-third capacity and 0.6 at full capacity. Simulations projected seasonal gas cooling COP's of 1.3 in Dallas and 1.6 in Chicago and heating COP's of 1.7 and 1.45, respectively.

Arthur D. Little were involved in the development of a solid desiccant dehumidifier that integrates with a residential electric air conditioning system. This unit was to have been laboratory tested in 1988 (4.6). A report on this work is not available at this time.

4.3 COMMERCIAL

GRI (4.6) has recently sponsored four commercial desiccant-based cooling developments. Two of these are large-scale systems developed by Cargocaire/Tecogen and Kathabar, for integration with electric chillers to provide total capacities between 20 and 100 tons. One is solid desiccant-based while the other uses a liquid desiccant. A third development, by Battelle and Gas Energy Inc., is an even larger system (> 100 tons) that is to be integrated with an absorption chiller. The fourth development is a 5 ton total gas-fired system, by Tecogen.

Cargocaire/Tecogen In the early 1980's Thermo Electron (under GRI sponsorship) and Cargocaire independently developed and installed desiccant dehumidification systems for integration with grocery store air conditioning systems (4.7). GRI subsequently funded further development of the Cargocaire System (with Tecogen Division of Thermo Electron participation) which resulted in the Superaire product. A total of 135 of these units were sold.

Monitoring of two installations in 1986/87 showed up to a 30-40% reduction in air conditioning electrical consumption with total annual energy costs being reduced 10-15% (4.8),(4.6). Other benefits of the system include greater comfort for shoppers, enhanced appearance of frozen foods, reduced display case refrigeration costs and avoidance of wet-coil health concerns. The improved latent capacity of the system also allows lower air flow rates to be used with associated cost savings in duct installation and fan operating costs. More than 70 units have been sold to more than 18 supermarket chains. Payback periods of two years or less are reported (4.6).

A Cargocaire HC-2250 dehumidifier was installed on a McDonalds Restaurant in Houston, Texas and monitored for approximately one year (4.9). While the conventional rooftop air conditioning system was unable to maintain design conditions (particularly relative humidity) the addition of the desiccant dehumidifier corrected this. However, it proved to be too expensive, inefficient and unreliable for widespread application in the restaurant industry. Potential benefits such as improved staff performance and higher sales were not quantified.

Three additional developments are known to be underway at this time. **Tecogen** performed a laboratory evaluation of a 5 ton, total-gas, solid desiccant system in 1987/88 (4.6). A report on this work is not yet available. **Kathabar Systems** of Somerset Technologies, Inc. (the leading U.S. manufacturer of liquid desiccant equipment) was to have performed a field experiment on their 5000 cfm make-up air dehumidification unit in 1988. Lower cost component development has been initiated. **Battelle Columbus** and **Gas Energy Inc.** (U.S. Hitachi Distributor) are developing an all gas, absorption chiller-integrated system (> 100 tons) for central applications in high rise commercial buildings. A subscale unit was to have been evaluated in the laboratory in 1988 (4.6). The project has been terminated because of a lack of manufacturer participation and concerns over high initial costs.

Gershon Meckler Associates have designed desiccant-based HVAC systems that are operating in large and medium size office buildings. They have patents on application techniques for new ways of integrating existing components and materials to improve economics of desiccant HVAC systems.

The systems use desiccants to dehumidify ventilation primary air and are combined with engine chillers which provide sensible cooling. Incoming outside air for ventilation is dehumidified in a two-stage desiccant wheel conditioner, then precooled and aftercooled by the engine-driven chiller. It is then saturated with non-refrigerated water, in an air washer, to drop the air temperature to as low as 5 °C. This cold air is distributed in variable volume to fan induction coil terminals throughout the building to provide cooling. First stage desiccant wheel regeneration heat is provided by relatively dry building exhaust air. In the second-stage, regeneration heat is provided by the heat recovered from the engine. When the chiller is not operating, regeneration heat is provided by a gas boiler. Desiccants used by Meckler Associates are silica gel in the first stage wheel, silica gel or lithium chloride or a combination in the second wheel.

Meckler predicts significant reductions in both energy and demand costs with the system described above. Based on a study of a 16000 m^2 office building in New Jersey, Meckler claimed 20 percent additional demand cost reductions than would be achieved by a cold air, variable air volume system with partial ice storage, in the building studied. This amounted to savings of $8000. In addition, system energy savings of about 20 percent or $37,000 were also predicted. The system, however, required a utility incentive grant of $13.50 per square metre of floor area to be comparable in first cost to the variable air volume system.

Meckler has also reported on a similar system intended for small commercial building establishments, but combined with an evaporative air washer, instead of a gas engine-driven chiller. He compared the performance of this system with an air-to-air heat pump. An annual energy cost reduction of 40 percent was predicted, together with a 70 percent electric demand reduction, for a total operating cost reduction of 40% in a 200 m^2 fast food restaurant.

5. ENVIRONMENTAL ASPECTS

Gas-fired cooling and heat pump systems can potentially benefit the environment in several ways:

(i) Some gas-fired cooling technologies do not use CFCs, but rather non-ozone damaging working fluids. Less damage to the ozone layer results as the leakage/release of ozone-depleting substances is avoided whenever this type of equipment replaces or displaces its conventional counterpart.

(ii) The net production of "greenhouse gases" such as CO_2, NO_x, etc. can be reduced in certain circumstances when the gas-fired cooling technologies used produce less of these gases than the generation of electric power or the burning of fuel in a furnace, that would otherwise be needed to produce the same effect.

(iii) Under certain circumstances the use of gas-fired equipment will result in lower primary energy consumption than conventional equipment. Associated with this reduction are the benefits of not having to extract or mine as much fuel and transport or transmit as much energy to the point of use.

(iv) The peak demand for electricity may be limited through the use of gas-fired cooling and heat pump equipment, thereby reducing the number of new electric generating stations and transmission lines required and the impact of construction of these facilities on the environment.

(v) Desiccant cooling systems can positively impact on the building environment as well. Inadequate ventilation levels can be improved while minimizing the energy impact associated with increased ventilation. Moisture levels can be reduced without overcooling conditioned air or the use of reheat.

The literature obtained and reviewed generally does not treat these considerations adequately. However, it does provide us with the basis upon which most of these benefits may be assessed. This section of the literature review will therefore focus on the method proposed to assess environmental benefits, the identification of both the relevant information that has been uncovered and the remaining data that must be obtained.

5.1 CFC EMISSIONS

In Canada 45-50 percent of CFC usage is in HVAC and refrigeration applications. Some refrigerants used in conventional electrically-driven and gas-fired systems, CFC-12 and CFC-11 in particular, are major contributors to the ozone depletion problem. CFCs are also significant contributors to the greenhouse effect (about 25% (5.1)) that is treated in Section 5.2. While many systems use HCFC-22, large chillers use either CFC-11, CFC-12 or CFC-114. Absorption-based chillers do not use CFC refrigerants and their application would reduce CFC emissions.

Desiccant dehumidification, a non-refrigerant based cooling technology, when used in combination with conventional electric cooling equipment, can reduce the use of chlorofluorocarbons and hydrochlorofluorocarbons refrigerants such as R11, R12 and R22. In small buildings, desiccant dehumidifiers can be combined with evaporative cooling equipment to eliminate the use of refrigerants entirely. The same system could lead to significant reductions in harmful gases emitted by fossil-fuel fired power plants, as well. The heat required for regeneration can come entirely from sources other than electricity, such as natural gas, recovered heat or solar energy.

Typical rates of refrigerant release by gas-fired cooling equipment, during its service life (manufacture, installation, operation, servicing and decommissioning) have not been found in this literature review. Ritter (5.2) assumed that the total charge of a large vapour compression heat pump escapes to the atmosphere once during its 15 year lifetime. If more comprehensive data cannot be found on typical release rates or expected future release rates, this assumption will be used. CFC releases from conventional equipment will be estimated with typical refrigerant charge data from manufacturers. Relative ozone depletion potential data for various refrigerants are currently available (5.2, 5.3, 5.4) to allow emissions of various types to be related.

5.2 GREENHOUSE GASES

The operation of conventional electric cooling equipment causes generation/release of greenhouse gases both through leakage of CFCs and the production of gases such as CO_2, NO_x, SO_2, soot, CO and HC in the thermal generation of electricity with fossil fuels. To quantify these emissions it is necessary to know both the rate of their production in each type of power plant used (i.e. kg/GJ), the mix of power plants being used, the efficiency of transmission and distribution and the amount of electricity being consumed by the equipment. The consumption of electrical energy will be determined by Caneta computer simulations and the power generation and transmission related data are being sought from Energy, Mines and Resources Canada and Ontario Hydro.

For gas-fired cooling equipment there are two major cases: the combustion of gas to provide thermal energy to an absorption system and; the combustion of natural gas in an IC engine to provide mechanical power. When natural gas is burned for heat, the emissions may be assumed to be the same as those from a gas boiler. Meal (5.5) gives the emissions of NO_x, CO, HC and soot for both low and high efficiency (condensing) cases. While CO_2 emissions data are not provided in this reference they are available for conventional and high efficiency gas furnaces in Fairchild (5.3). Meal (5.5) also gives the non-CO_2 emissions for natural-gas-fired IC engines representing worst, typical and optimum cases. It is believed that CO_2 emissions from gas engines can be determined from other data.

For both gas and electric cooling equipment that use CFCs, or HFCs, the expected refrigerant leakage will be estimated, as discussed in 5.1, and the relative greenhouse potential for that refrigerant (5.2, 5.3) will be used to arrive at an "equivalent" (in the terms of greenhouse effect) amount of CO_2. The equivalent amounts of CO_2 for each of the greenhouse gasses may be summed to arrive at a net equivalent greenhouse effect (in kg CO_2).

5.3 PRIMARY ENERGY CONSUMPTION

Caneta computer simulations will determine the amount of energy consumed at point of use. These may be converted to primary energy use through efficiencies of transmission and generation or production. The use of less primary energy to complete a given task results in a net saving of energy. In general this implies that less coal, uranium, oil or gas are extracted from the earth and environmental benefits ensue even though they may be difficult to quantify.

5.4 ELECTRICAL DEMAND REDUCTION

Gas-fired cooling technologies hold substantial potential to reduce electrical power demand as discussed in Section 6.0. When such demand reductions are coincident with the system peak, the economic benefit may be measured in terms of an avoided cost of constructing new generating and transmission facilities. The environmental benefit is more difficult to quantify but it is associated with avoiding damage related to the construction of the same new generating and transmission facilities.

6. DEMAND-SIDE MANAGEMENT OPPORTUNITIES

In the past few years, natural gas utilities have been studying how gas-fired cooling can meet the criteria or needs of electric utility demand-side management programs. In Ontario, for example, while the province as a whole is electricity winter-peaking, there are major centres, such as the City of Toronto, which are summer peaking. This summer peak is due to commercial building cooling.

Gas utilities, on the other hand, have winter demand peaks and significant summer demand valleys. Both utilities would derive significant benefits from increased penetration of gas-fired cooling technology.

American Gas Association (AGA) (6.1, 6.2) have identified that commercial office buildings peak electricity demand due to cooling can be eliminated altogether by using natural gas air conditioning equipment. Depending on the associated electricity demand charges, the electrical demand cost reduction can yield customer payback periods under 3 years, for gas-engine-driven chillers. At the same time, electric utility capital costs associated with providing capacity to meet the peak demand are avoided. These costs were found to vary from $500 to $800 per kW and would represent an avoided cost of anywhere from $100,000 to $180,000 for a typical commercial office building, with a design cooling requirement of 150 tons.

Other demand-side management options examined by AGA included gas-fired desiccant systems combined with electric air conditioning equipment. The conventional electric air conditioner can be downsized by sizing the desiccant system to meet the latent cooling load, while the sensible load only is met with electricity. This can result in a significant electrical demand reduction.

One other hybrid system or combination plant would involve the use of an electric chiller to meet baseload cooling needs, while a gas-fired absorption chiller would be used to meet peak cooling demands. This system takes advantage of the lower energy cost of electric chiller operation, while avoiding high electrical demand costs, at peak times with an absorption chiller.

7. CONCLUSIONS

Most gas-fired cooling and heat pump developments funded by GRI or DOE have not led to product commercialization, as of 1990. Exceptions are the Tecogen engine-driven chiller and the Thermo King gas-fired engine driven rooftop unit. The success of these two, particularly the Tecogen chiller, is likely due to the fact that in large office buildings electrical demand charges are largely due to cooling. Even though electric chillers are more energy-efficient, electrical demand charges are high and this leads to lower operating costs with engine-driven chillers and reasonable payback periods.

Developments targeted to the residential market cannot rely on electrical demand charges to help improve the economics. Instead, high efficiency is needed, together with lower capital cost, to improve the competitiveness of gas-fired cooling. All single-effect absorption developments by GRI and DOE have been stopped, in favour of double-effect or more efficient cycles, such as the GAX. The emphasis is also on heat pump developments which, because of greater utilization, will increase operating cost savings and better justify the higher capital costs, compared to competing electric and gas alternatives, particularly in northern climates.

Gas-fired cooling promises significant load-levelling benefits to both utilities. Summer peaking electric utilities and winter peaking gas utilities should mutually benefit from reduced summer cooling peak and summer valley filling, respectively. A portion of the avoided cost of new generation capacity could be used to encourage gas-fired cooling in such locales. The gas-utility benefits from increased sales and better utilization of existing facilities.

The desiccant-based equipment developments appear to be attractive in cooling applications with high latent to sensible loads or where a low humidity level is desired (e.g. supermarkets, sensitive manufacturing areas, some storage applications). In other cooling applications, desiccant dehumidification can be combined with vapour compression equipment to permit smaller electric-driven compressors with lower electrical demand. Relatively high cost has to-date prevented widespread application of desiccant cooling systems.

Gas-fired cooling and heat pump equipment application can potentially benefit the environment in many ways, such as: the working fluids can be non-ozone depleting greenhouse gases produced can be less and resource energy-efficiency can be higher than with competing systems. By reducing the need for new generation facilities, the impact of construction of such facilities on the environment is lessened.

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Table 1 Absorption Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost [$US]	Absorption Cycle Type	Configuration	Status
Residential								
Arkla (DOE)	1.25	-	24	63	$4,000 [1981]	Single Effect	Split-System Heat Pump	Development stopped - not cost effective
Arkla (DOE)	-	0.72	36	-	-	Single Effect	Split-System Air Conditioning	Unknown
Allied (GRI/DOE)	1.25	0.50	36	90	$4,000 [1981]	Single Effect	Split-System Heat Pump	Development stopped - not cost effective
Columbia Gas (GRI)	1.50	0.80	36	66	$3,400 [1986]	Double Effect	Split-System Heat Pump	Field testing in 1991
Phillips (DOE)	1.80	0.90	36	-	$2800-$3000 [1989]	GAX	Split-System Heat Pump	Field testing in 1991
Battelle (GRI)	1.80	0.84	18 to 36	-	$4,600 [1985]	Dual-Cycle Double Effect	Split-System Heat Pump	Field testing delayed
Battelle (GRI)	0.85	1.00	36	27	-	Double Effect	Split-System Air Conditioning	Field testing 1992
Commercial								
Carrier (DOE)	1.76	1.02	> 1200	-	20% more than conventional	Dual-Loop Double Effect	Heat Pump	Development stopped - not cost effective
Trane (GRI)	1.61	0.80	1,860	-	-	GAX	Heat Pump	Development stopped - not cost effective
Trane (GRI)	-	1.50	> 1800	-	-	Triple Effect	Chiller	Proof of concept planned for 91
Apache	-	-	< 1800	-	-	Triple Effect	Cogen-chiller	Unknown

*** Capacity in MBtu/h can be converted to kW by multiplying by 0.293**

Table 2 Engine-Driven Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost	Engine Type (Compressor Type)	Configuration	Status
Residential								
M.T.I. (GRI,DOE)	1.62	0.91	36	63	-	Free-Piston Stirling (Hydraulically-coupled vapor compression)	Split-System Heat Pump	Performance demonstrated in laboratory. Design for heat pump prototype to be defined.
Sunpower Inc. (GRI,DOE)	-	-	-	-	-	Free-Piston Stirling (Magnetically-coupled vapor compression)	-	Development has concentrated on the drive/compressor. Unit has not been built up.
Commercial								
Thermo King (GRI,AGA)	-	0.77	180	216	$17,500	4 cylinder Hercules NG 1600 (4 cylinder reciprocating R22)	Rooftop HVAC Unit	Commercially available in 1990 for field trials.
Tecogen	-	1.40	1,800	-	N.A	Modified 454 cu.in. G.M V-8 (Howden Twin Screw)	Chiller	Commercially available since 1988 (Tecochill CH-150)
Tectonics	1.90	1.10	180	-	-	Linear (Braun) BR-105 R.2 (vapor compressor)	Rooftop Heat Pump	Under field trials
Stirling Power Systems (GRI)	1.40	1.00	120	N.A	-	Kinematic Stirling (mechanically-driven) Open-Drive reciprocating	Rooftop Heat Pump	York International no longer involved. Development now with Italian H.P. manufacturer.

* Capacity in MBtu/h can be converted to kW by multiplying by 0.293

Table 3 Desiccant-Based Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost [$US]	Configuration	Desiccant Type	Status
Residential								
Tecogen and Kathabar Systems (GRI)	-	0.50 - 0.60	12 to 18 (latent)	-	$550 (desiccant unit only)*	Integrated Open-Cycle	Liquid (Lithium Chloride)	Laboratory and field tests have been performed. Next phase is unit commercialization.
Zeopower and Thermax (GRI)	1.40 - 1.70	1.30 - 1.60	18 to 36	-	$2,000 (factory cost)	Total Closed-Cycle	Solid (Zeolite)	Laboratory evaluation and simulation
Arthur D. Little (GRI)	-	-	30	-	-	Integrated Open-Cycle	Solid (-)	Laboratory evaluation
Commercial								
Tecogen and Cargocaire (GRI)	-	-	240 to 960	-	-	Integrated Open-Cycle	Solid (Lithium Chloride)	70 'SuperAire' units installed in 18 U.S. supermarket chains (1988) Field evaluation of HC2250 unit in a MacDonald's restaurant
Tecogen (GRI)	-		60	-	-	Total	Solid (-)	Laboratory evaluation
Kathabar Systems (GRI)	-	-	240 to 1,200	-	-	Integrated Open-Cycle	Liquid (-)	Field experiment
Battelle and Gas Energy Inc. (GRI)	-	-	> 1,200	-	-	Integrated with absorption chiller	- (-)	Subscale laboratory evaluation

*** Capacity in MBtu/h can be converted to kW by multiplying by 0.293**

APPENDIX B

UPDATE ON GAS-FIRED COOLING TECHNOLOGY DEVELOPMENTS

UPDATE ON GAS-FIRED COOLING TECHNOLOGY DEVELOPMENTS

1. INTRODUCTION

The second phase of this investigation of gas-fired cooling involved establishing telephone contact with the technology developers, or sponsoring organizations, of those developments identified in Phase 1. In this manner, one can obtain an up-to-date status of the various projects.

The following sections present the results of these telephone interviews. At the end of this update a contact list identifies the individuals contacted, complete with their affiliations and phone numbers.

2. ABSORPTION EQUIPMENT

Of the absorption cooling developments identified in Phase 1 of this investigation, research is continuing of five projects, three of which are residential and the other two are commercial. All five developments incorporate advanced systems: both commercial projects are triple-effect, two of the residential projects are double effect, and the third involves generator/absorber heat exchange. The following is a summary of the telephone discussions with the organizations whose development status was reported in Phase 1 as either ongoing or unknown.

2.1 RESIDENTIAL

Approximately one hundred direct evaporatively-cooled absorption chillers for the residential market were produced by Arkla Industries Incorporated, now owned by the **Dometic Corporation**. When government support of the solar industry was abandoned in the early 1980's, so was further support and development of this chiller by Arkla Industries.

A manufacturer has not been found to support development of the **Columbia Gas System Service Corporation** double effect heat pump, yet interest has been shown, according to a contact at Columbia Gas. The development is currently in the laboratory stage, attempting to achieve a partially contained unit. Plans are for a self-contained unit ready for field testing in 1991. The estimated cost of the unit has increased to the $5000 range, but research into optimizing the components, i.e. decreasing the size of the heat exchangers, may reduce this amount. Such optimization may lower the performance of the system. This is tolerable, since laboratory tests have shown the performance to be improved over the original published figures of a COP of 1.50 in heating and 0.80 in cooling.

Phillips Engineering Company are in the process of negotiating a working arrangement with Lennox Industries for further development of Phillip's absorption heat pump. The predicted performance of the unit has not yet been achieved on a packaged system. Research is continuing on the system components and their integration, concentrating on the performance of the generator/absorber heat exchanger and reducing the size of the absorber (currently five feet in length). Phillips is planning to start field testing in the first quarter of 1991.

Battelle Columbus Division's dual cycle, double effect heat pump was developed to the point of a packaged prototype ready for field testing, but the project was cancelled due to a lack of manufacturer's interest and escalating costs.

Battelle Columbus Division's double effect air conditioner is still under development and because it is a simpler system than the dual cycle heat pump, it is more cost effective. The company has demonstrated an integrated breadboard unit which has achieved the targeted COP's of 0.85 in heating and 1.00 in cooling. Battelle is planning a laboratory durability test of a prototype for 1992-1993. The unit is estimated to be comparable in first cost to a medium to high efficiency gas furnace with electric air conditioning.

2.2 COMMERCIAL

The triple effect chiller, being developed by the **Trane Company**, is still in the research and development phase; equipment has not yet been built. A laboratory prototype (proof of concept) is planned for 1991, with field testing expected in 1992 or 1993. Development is continuing on the refrigerants for this cycle with support from Oak Ridge National Laboratory.

Modular Co-generation Corporation, in a joint venture with **Apache**, is developing an absorption co-generation chiller which uses an ammonia ejector for jet refrigeration. The system utilizes low temperature steam, produced from the exhaust heat of an internal combustion engine, to run a turbo compressor directly coupled to a turbine. Research is concentrating on increasing the ejector COP from about 0.3 to 0.5, and on identifying refrigerants for high temperature use. A proof of concept of the system is planned for spring of 1991 with testing of a built system set for late 1991. Initially a double effect chiller will be incorporated into the system with a switch to a triple effect chiller planned for about two years later. The Department of Energy through Brookhaven National Labs (BNL) is assisting in funding this development.

3. ENGINE-DRIVEN EQUIPMENT

The literature review in Phase 1, had identified six different gas-fired engine-driven developments, at various stages of development, sponsored by GRI or DOE. An additional project involving GRI, Briggs and Stratton, Honeywell and York International was also identified, but no published information was available. Telephone contact with the sponsors or developers was seen as important to update the status of these developments.

3.1 RESIDENTIAL

Contact was established with GRI to obtain their perspective on the developments covered by the Phase 1 Literature Review. According to the contact, the M.T.I. hydraulically-coupled FPSE development was no longer supported by GRI. No specific reason for this turn of events was given. The same contact reported that the Sunpower Inc. magnetically-coupled unit has also been abandoned by GRI, because the sales volumes required to make the project viable, did not appear to be feasible.

As ORNL had been involved in both the M.T.I. and Sunpower Inc. developments, contact was established to determine whether the activities were still on-going. ORNL, while acknowledging that GRI was no longer funding either development, the DOE, through ORNL, continued to support both projects. However, neither project had reached the stage of system prototype. Both projects were continuing component improvements and development. The hydraulic transmission used originally in the M.T.I. Free-Piston Stirling engine (FPSE) had been abandoned, due to complications and cost, in favour of a magnetically-coupled compressor. According to ORNL, M.T.I. did a design study and cost estimate for this new version. At the present time, efforts are continuing with DOE and ORNL support to cost-optimize the combustor in the M.T.I. unit.

Sunpower Inc. is continuing the development of their FPSE. In the last phase, both the engine and compressor worked well alone. When the two were combined there were difficulties starting the engine. DOE and ORNL are continuing their support of the Sunpower development.

The GRI contact described two residential/small commercial projects that were being pursued at this time, a three ton engine-driven development and a 5 ton light commercial engine-driven unit. The former involved Battelle-Columbus, York International, Briggs and Stratton, Honeywell and Copeland. Six to ten units were being installed for field trials, with GRI support. The latter is a unit manufactured by Aisin Seiki Co. Ltd. of Japan. GRI are looking at modifying this unit, as it does not perform as well under United States climatic conditions, as expected.

The Battelle et al development uses a Copeland R22 hermetic compressor, redesigned for open-shaft service. The Briggs and Stratton reciprocating engine is designed for longevity. Other features mentioned included a variable-speed indoor fan motor and a two-speed outdoor fan motor both to reduce electrical energy consumption. The engine employs lean burn combustion to minimize NOx emissions. The claimed seasonal performance is a COP_H and COP_C of 1.3.

3.2 COMMERCIAL

The commercial engine-driven developments identified in the literature review were also followed-up on in this Phase. According to GRI, the Stirling Power Systems, stirling engine driven roof-top heat pump is no longer being supported. The GRI contact did not know what the status of the Tectonic's linear engine development was, but suggested contacting ORNL.

The ORNL contact stated that the Tectonics Linear engine-driven heat pump development was continuing. Efforts had concentrated on developing an improved refrigerant seal. A bellows type seal had been developed and had shown promise. However, it did not have the required durability when the engine and compressor operated together. Work is continuing on the seal and the starting system. This development has not advanced to the prototype stage, as of yet, and remains at the component development level.

The Thermo King engine driven roof-top air conditioner field trials were due to be completed by October 1990. A report would be available shortly. The Tecogen chiller development was on-going. They were now jointly developing 250 and 500 ton centrifugal compressor units with Carrier Corporation. Tecogen were also involved in developing an engine-driven 25 ton roof-top unit.

Another development mentioned by GRI involved Trane and Hercules, an engine manufacturer. The two companies were working on 55,80 and 100 ton engine-driven chillers. They were also examining the feasibility of integrating these chillers with an ice-storage system. American Gas Association laboratories are also involved in this development.

4. DESICCANT BASED-COOLING PROCESSES

In the Phase 1 literature review, GRI was clearly identified as the driving force behind North American developments in desiccant-based cooling processes. Contact was therefore established with GRI[1] in order to obtain an update on the status of the seven equipment development projects identified earlier. In the residential area, of three product development efforts one has been terminated, another redefined, the third expanded in scope and a new project has been initiated. In the commercial area, of four product development efforts one is viewed as complete with a successful commercialized product being sold. However, product variations to expand the market area are underway.

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[1] It is interesting to note that the Senior Project Manager, Desiccant Technology has left GRI to join a manufacturer of desiccant-based equipment.

Another development continues and two others have been terminated.

4.1 RESIDENTIAL

Bacchus, a manufacturer of evaporative coolers, has joined **Tecogen** in the commercialization of a low-cost residential cooling system. The product development has evolved from an integrated to a total (all-gas) liquid-desiccant-assisted evaporative cooler, aimed at dry climate regions (the U.S. Southwest, Northwest and California). It extends the operation of evaporative coolers into more humid conditions/regions. Current efforts in this development, which was redirected by manufacturer interest, are to develop, test and refine a laboratory prototype of the low-cost, low COP system.

The **Zeopower and Thermax** heat pump development has been terminated. Problems with the reliability and manufacturability of the serpentine heat exchangers led to the decision to focus on a new zeolite heat exchanger development.

Two laboratory prototypes of the **Arthur D. Little** integrated solid-desiccant dehumidifier system have been fabricated and test results on the first confirm a projected COP of 0.6. While the net latent capacity is below design, as is the EER, these shortfalls are expected to be overcome in the second prototype.

A derivative of this development is a stand alone desiccant dehumidifier targeted at the retrofit market, that would use an existing water heater to supply regeneration energy. First tests indicate that 70 lbs of moisture per day may be removed and a thermal COP of 0.45 was measured. A manufacturing partner will be sought.

A new privately-funded development of a lithium bromide, liquid desiccant-based air conditioner by **Albers Technologies** is being tested at the American Gas Association Laboratories.

4.2 COMMERCIAL

The **Cargocaire** Superaire product continues to be applied with over 135 units installed in over 35 U.S. supermarket chains, as of January 1990. A derivative of this product, to provide humidity control and avoid mould and mildew damage in hotels, motels and similar buildings, is under development by Cargocaire with GRI support.

A manufacturer, **Air Distribution Associates**, joined forces with **Tecogen** after breadboard system testing demonstrated proof of concept by achieving an ARI thermal COP of 0.95. Design enhancements to reach a target COP of 1.0 were defined. Laboratory prototypes performed significantly under the design COP of 1.0 and capacity of 5 tons, due largely to non-uniform air flow. As the first cost of the proposed new design was estimated to be significantly higher than conventional vapour compression systems this project will not proceed to field testing and commercialization.

Two **Kathabar Systems,** integrated liquid-desiccant rooftop systems, for low rise commercial and institutional buildings, were manufactured and field tested. Both units operated below projected capacities and efficiencies, at part-load, due to the lack of wicking surfaces in the three-way heat exchanger and to oversized pumps and fans. Swimming pools and ice rinks are seen as initial niche markets but further cost reductions are needed to compete in the general HVAC market. Development of plastic and fiber reinforced plastic components has been initiated to this end.

The **Battelle/GasEnergy Inc.** development of a liquid-desiccant system integrated with an absorption chiller has been terminated due to lack of manufacturer commitment and concerns over high system first cost.

5. CONCLUSIONS

Recent contacts with GRI, ORNL, Columbia Gas System Corporation and the various technology developers and manufacturers has provided up-to-date status of the gas-fired equipment developments reported on in Phase 1. There have been significant changes in some developments due to technological difficulties involving either a complete change in direction or cancellation. In other cases, the results are encouraging and the equipment is about to be field tested with a manufacturers' involvement.

In the absorption equipment area, the Phillips Engineering Company's heat pump development appears the most promising. Lennox Industries apparently have a new arrangement with Phillips to assist in subsequent prototype development phases. The unit promises better performance and a lower estimated cost than the Columbia Gas System Corporation design, as well. Both the Trane and Apache triple effect chiller developments appear promising for commercial building cooling and cogeneration applications, respectively.

The most promising engine-driven residential market development appears to be that involving Battelle, Briggs and Stratton, Honeywell, Copeland and York International. Six to ten three ton heat pumps will be field tested with GRI support. None of the FPSE developments has advanced beyond the component design or development stage. The Department of Energy continue to provide support to this area, through ORNL. The free-piston stirling engine driven heat pump, however, is viewed as only a long term development, at best.

Commercial engine-driven chiller developments are promising. Tecogen are jointly developing centrifugal compressor chillers with Carrier. Trane and Hercules are working together on engine-driven chillers for Trane's product line.

The desiccant-based equipment developments have been most successful in the supermarket applications. Potential to further expand into niche markets such as hotels/models and restaurants is also possible.

One development to watch is the Bacchus/Tecogen development of a desiccant-based dehumidifier-enhanced, evaporative cooler. This product could extend the market for the traditional evaporative cooler to other, less dry residential cooling markets. Further development and testing is needed to confirm this conclusion.

All gas-fired commercial equipment implementation potential could be enhanced significantly if electrical demand reduction incentives were available for dual-fuel or fuel substitution applications.

UPDATE CONTACTS

1. Dometic Corporation, (812)424-1800
2. Columbia Gas System Corporation, Howard Meacham, (614) 481-1445
3. Phillips Engineering, Robert McQuiston, (616)983-3935
4. Battelle Columbus Division, David Ball, (614)424-4901
5. Trane Company, Robert Modahl, (608)787-2711
6. Trane Company, Mike Byars, (608)787-2000
7. Modular Cogeneration Corporation, Angelo Skalafuris, (914)668-9108
8. Oak Ridge National Laboratory, Fred Creswick, (615)574-2009
9. Oak Ridge National Laboratory, Robert DeVault, (615)574-0738
10. Gas Research Institute, Bill Dolan, (312)399-8359
11. Gas Research Institute, Bill Ryan, (312)399-8376
12. Gas Research Institute, Bruce Lindsay, (312)399-8100
13. Gas Research Institute, Davor Novosel, (312)399-8258

Table 1 Update on Absorption Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost [$US]	Absorption Cycle Type	Configuration	Status
Residential								
Columbia Gas (GRI)	>1.50	>0.80	36	66	$5000-$5500 [1990]	Double Effect	Split-System Heat Pump	Field testing in 1991 No manufacturer involvement
Phillips (DOE/ORNL)	1.80	0.90	36	-	$2800-$3000 [1989]	GAX	Split-System Heat Pump	Field testing in 1991 Lennox Industries is involved
Battelle (GRI)	0.85	1.00	36	27	-	Double Effect	Split-System Air Conditioning	Prototype durability testing in 1992
Commercial								
Trane (GRI)	-	1.4-1.5	> 1800	-	-	Triple Effect	Chiller	Prototype planned for 1991 Field testing in 1992
Apache (DOE/BNL)	-	-	< 1800	-	-	Triple Effect	Cogen-chiller	Proof of concept in 1991

See Phase 1 report for a list including discontinued developments.

*** Capacity in MBtu/h can be converted to kW by multiplying by 0.293**

Table 2 Update on Engine-Driven Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost	Engine Type (Compressor Type)	Configuration	Status
Residential								
M.T.I. (DOE)	1.62	0.91	36	63	-	Free-Piston Stirling (Magnetically-coupled)	Split-System Heat Pump	Latest design uses magnetic coupling. Efforts to cost optimize combustor.
Sunpower Inc. (DOE)	-	-	-	-	-	Free-Piston Stirling (Magnetically-coupled)	-	Difficulty starting engine. Compressor/drive needs work.
Batelle et. al. (GRI)	1.30	1.30	36	-	-	Internal combustion (lean burn)	Split-System Heat Pump	Six to ten units will go to field trials.
Commercial								
Thermo King (GRI,AGA)	-	0.77	180	216	$17,500	4 cylinder Hercules NG 1600 (4 cylinder reciprocating R22)	Rooftop HVAC Unit	Report on field trials due shortly. Commercially available.
Tecogen (GRI)	-	1.40	1,800	-	-	Modified 454 cu.in. G.M V-8 (Howden Twin Screw)	Chiller	New joint developments with Carrier.
Tectonics (DOE)	1.90	1.10	180	-	-	Linear (Braun) BR-105 R.2 (vapor compressor)	Rooftop Heat Pump	Never made field trials. Component development, work on starting system continue.
Stirling Power Systems	1.40	1.00	120	-	-	Kinematic Stirling (mechanically-driven) Open-Drive reciprocating	Rooftop Heat Pump	Development now with Italian H.P. manufacturer. GRI support discontinued.

* Capacity in MBtu/h can be converted to kW by multiplying by 0.293

Table 3 Update on Desiccant-Based Equipment Developments

Developer (Sponsor)	COPh	COPc	Cooling Capacity MBtu/h*	Heating Capacity MBtu/h*	Retail Cost [$US]	Configuration	Desiccant Type	Status
Residential								
Bacchus and Tecogen (GRI)	-	0.50 - 0.60	36 (total)	-	Competitive w/ electric A/C	Total, Open-cycle : Evap. Cooler + Desic.	Liquid (Lithium Chloride)	Field testing of 3 units completed Laboratory hardware development
Arthur D.Little and Herrmidifier (GRI)	-	0.45	70 lb H2O/day	-	600	Water heater powered Dehumidifier	Solid (-)	Hardware concept definition
Albers Technologies	-	NA	12	-	NA	Total	Liquid (Lithium Bromide)	Laboratory evaluation at the American Gas Association
Commercial								
Cargocaire (GRI)	-	-	240 to 840	-	No premium	Integrated, Open-cycle : for supermarkets	Solid (Lithium Chloride)	>180 'SuperAire' units installed in >35 U.S. supermarket chains (1990).
Cargocaire (GRI)	-	-	6000 scfm	-	NA	Make-up air unit w/ electric A/C for hotels only	Solid (Silica gel)	Field demonstration at a Marriott Courtyard
Cargocaire (GRI)	-	-	4000 scfm	-	NA	Make-up air unit w/ electric A/C for quick service restaurants only	Solid (Lithium Chloride)	Field demonstration at a Houston McDonald's completed; alternate system development w/ ADA/Kathabar
ADA/Kathabar Systems (GRI)	0.78	0.50	480 1,200	400	NA	Total system for quick service restaurants only	Liquid (Lithium Chloride)	Laboratory evaluation
ICC Technologies	-	-	up to 500 lb H2O/day	-	1.9 - 3.6 year payback	Integrated, Open-cycle : Make-up air unit	Solid (Silica gel)	To be installed in 25 supermarkets (1990)

*** Capacity in MBtu/h can be converted to kW by multiplying by 0.293**

*** Capacity in lb H2O/day can be converted to kg H2O/day by multiplying by 0.454**

APPENDIX C

PERFORMANCE AND ECONOMIC ATTRACTIVENESS OF GAS COOLING COMPARED TO ELECTRIC COOLING IN CANADIAN BUILDINGS

PERFORMANCE AND ECONOMIC ATTRACTIVENESS OF GAS COOLING COMPARED TO ELECTRIC COOLING IN CANADIAN BUILDINGS

1. INTRODUCTION

The current phase of this investigation of gas-fired cooling was to assess the performance and economic attractiveness of gas cooling compared to electric cooling in commercial and residential buildings in a Canadian city, through computer simulation. For the purpose of assessing the relative merits of the competing cooling systems, a microcomputer version of the building energy analysis program DOE 2.1D (by ADM Associates) was selected. This latest version of the program was known to model gas-fired cooling systems of interest and the DOE program is generally recognized as an industry standard, particularly for investigations of this nature.

Representative office buildings were selected for the simulation runs. Toronto weather data for the 1983 calendar year was employed to drive the simulation. Typical electric cooling plants and hvac systems were selected as representative of equipment commonly used in these buildings. State-of-the art performance levels were assumed for all equipment. Both City of Toronto and City of North York electricity and gas rates were used to examine the impact of both high and average electricity rates, respectively.

The performance and economic attractiveness of a residential single family home equipped with a gas-fired, engine-driven heat pump, compared to that of a state-of-the art air-source heat pump will be the subject of additional modelling efforts, in a final phase of this project. The results will be incorporated into the final report.

2. BUILDING AND SYSTEM/DESCRIPTIONS

A medium and large office building were selected for the simulation runs. Brief descriptions, design conditions and loads are shown in Figure 1 and Figure 2. Both buildings were assumed to be located in the Toronto area.

2.1 HVAC PLANT AND SYSTEMS - MEDIUM OFFICE BUILDING

The gas-fired cooling option selected for the medium building was an engine-driven chiller, with a coefficient of performance of 1.3, similar to that of the commercially available Tecogen chiller. The distribution system was dual-duct, variable air volume in both the building perimeter, and core. An air-side economizer was included in the system. Night setback and night setup to 12°C and 32°C, respectively, are implemented in the building.

The heating plant was a gas-fired hot water boiler which supplied hot water to fan-coil units throughout the building. The cooling plant supplies chilled water to separate fan-coil units, for cooling purposes.

Condenser heat from the engine-driven chiller was rejected to a cooling tower. The engine-driven chiller has an engine waste heat recovery option, the performance of which was modelled in some simulation runs.

A hermetic reciprocating chiller with an EER of 14.4 at ARI Standard Rating conditions was selected as the electric cooling option for comparison. The distribution system and heating plant were common in both systems. While an air-side economizer was also employed, heat recovery via double-bundle condensers was not.

In addition to modelling the straight gas-fired, engine-driven chiller against the electric chiller, one combination plant composed of one gas-fired and one electric chiller was also modelled. The effect of using either the gas-fired or the electric chiller as the base load chiller in the plant was also examined. The electric chiller plant was modelled as having only one chiller, as well as two chillers of equal capacity. The impact of not using air-side economizers, on both electric and gas-fired cooling system operating costs was also investigated.

2.2 HVAC PLANT AND SYSTEMS - LARGE OFFICE BUILDING

The gas fired cooling option selected for the large building was a double-effect, direct-fired absorption chiller/heater, with a coefficient of performance of 1.0 on cooling and a heater efficiency of 90 percent. This unit is very similar to the commercially-available Hitachi chiller/heater, now distributed in North America by York International.

The distribution system, in the large building, was a four-pipe fancoil system in the perimeter, with a constant volume, variable-temperature system in the core, with fancoils for heating and cooling. An air-side economizer was included in the distribution system. As in the Medium Building, night setback and night setup to 12°C and 32°C, respectively, were employed, as appropriate.

A hermetic centrifugal chiller with an EER of 18.3 at Standard Rating conditions, was selected as the competing electric cooling option. The same distribution system, for both perimeter and core areas, was assumed, once again with the same air-side economizer, to allow for "free" cooling operation.

As with the Medium office building, combination chiller plants were modelled, once again examining the effect of using either the gas-fired chiller or the electric chiller, as the base load chiller. Simulations with and without the air-side economizer were also performed.

2.3 HVAC PLANT CAPITAL COST ESTIMATES

While the DOE 2.1D computer program provides operating cost estimates for the various competing systems, capital cost estimates and installing labour costs, both for the gas-fired and electric cooling equipment, needed to be established. Various information sources [1],[2],[3] were identified and compared before selecting appropriate values for the cost-benefit analysis.

By keeping the distribution systems common to both the gas-fired and electric cooling plants, the incremental capital cost could be calculated by comparing chiller capital and labour costs only. While this did not allow comparison to other attractive, common electric cooling options, such as a water-loop heat pump in the Medium office building, it would permit an initial estimate of the relative attractiveness of the gas-fired cooling alternatives.

The incremental capital cost estimates for the gas-fired cooling plants compared to the competing electric cooling plants are shown in Table 1 (a) for the Medium Office Building and Table 1 (b), for the Large Office Building. These costs are used later in this report to estimate the simple payback periods associated with the lower energy cost and/or electrical demand cost reductions resulting from the various gas-fired cooling systems modeled.

3. COMPETITIVE SYSTEM ENERGY USE AND ELECTRICAL DEMAND

The heating and cooling energy use, building electrical demand, and associated operating costs, are presented in Table 2 (a) for the systems examined in the Medium Office Building and in Table 2 (b) for the Large Office Building, in the City of North York. Tables 3 (a) and 3 (b) present results for the Medium Office Building and Large Office Building, respectively, in the City of Toronto.

While the City of North York and the City of Toronto are both within Metropolitan Toronto, the local electric utility rate structures are significantly different. While the heating and cooling energy use and billing peak demands would be identical in both cities in the same building, the operating costs are quite different. This permits a comparison of the impact of electrical rates on the economic attractiveness of gas-fired cooling without the need for two separate weather files. The natural gas rates are the same in both cities and are the rates published by the Consumers Gas Company. The utility rates are shown in Figure 2.

Finally, Figures 3, 4 and 5 present the simple payback periods for the more promising gas-fired cooling systems, in the two buildings, in the two cities. The effect of both electric utility demand-management incentives and gas utility incentives on simple payback periods are also presented.

3.1 DISCUSSION OF RESULTS

3.1.1 MEDIUM OFFICE BUILDING

On review of the simulation results for Systems 1 and 1 (a), in Tables 2 (a) and 3 (b), it becomes clear that the Medium Office Building should not be using an air-side economizer. In both cities, the total operating cost is lower without the economizer. The building winter billing peak demand is reduced by 13 kW by not using an economizer for free cooling. The Medium Building has a heating energy requirement in excess of the cooling energy requirement and the "free cooling" was obviously increasing the heating load in the building. The systems of interest are therefore those without the economizer option (1a, 2a, 3a).

The highest reduction in operating cost, in the Medium Office Building, relative to system 1a, is achieved by System 3 (a), which is the engine-driven chiller, with heat recovery from the engine cooling water. The heat recovery option, has negligible effect on winter billing peak demand. But, as with the other gas-fired cooling options, it achieved a significant peak demand reduction in summer (57 kW) and an annual electrical demand reduction of 312 kW.

Combination Plants

Systems 6 and 6 (a), in both Tables 2 (a) and 3 (a), are combination gas-fired and electric cooling plants. This approach was thought to offer promise to significantly reduce total operating cost compared to, say a plant composed of electric chillers (system 4), while having a lower incremental capital cost, than a plant of entirely gas-fired chillers.

In System 6, the electric chiller operated as the base load cooling plant. When cooling load exceeded the 42 ton capacity of the electric chiller, a matching 42 ton gas-fired engine-driven chiller operated in addition to the electric chiller to meet the cooling load.

In System 6 (a), the opposite was the case. The gas-fired engine-driven chiller was the base load plant, with the electric chiller only operating at times, when the load exceeded the capacity of the base load plant.

Comparing the performance results in Tables 2 (a) or 3 (a) to that for System 4, it is evident that there is no billing peak demand change in winter, for either system. In summer, there is a billing peak demand reduction for both Systems 6 and 6 (a), with only a slight advantage to System 6(a) (4kW). Total annual electrical demand reduction, is about 50 percent greater with System 6 (a) than with System 6 (69 kW). This latter result suggests that one gas-fired engine-driven chiller can meet most of the cooling load in the Medium Office Building. In fact, with System 5 which has 2-42 ton engine-driven chillers, the annual electrical demand reduction is only about 30% greater than with System 6 (a).

Economic Attractiveness

Figures 4 and 5 present simple payback periods for the more promising gas-fired cooling systems in the Medium Office Building. The engine-driven chiller, with engine cooling water heat recovery, (System 3 (a)) shows a simple payback period of just under 10 years, compared to the electric reciprocating chiller (System 1 (a)) using City of Toronto commercial electrical rates. In North York, the same system has a simple payback period of just under 20 years, due to the significantly lower electricity rates in the Borough compared to the City of Toronto.

Impact of Incentives

The application of the "Savings by Design" Ontario Hydro demand-management incentive, could have a dramatic impact on the economic attractiveness of gas cooling. In Figures 4 and 5 , the cross-hatched bars assume application of an incentive equal to 50% of the estimated incremental capital cost shown in Tables 1 (a) and 1 (b). The gas-fired systems reduce peak billing electrical demand sufficiently to qualify for this incentive, resulting in a halving of the simple payback period. System 3 (a), in the Medium Building, in the City of Toronto, has a simple payback period under 5 years with a one time incentive of about $25,000.

3.1.2 LARGE OFFICE BUILDING

The Large Office Building is characterized as having an annual cooling energy requirement three times greater than the heating energy requirement. In the Medium Office Building, the heating energy requirement was 40 percent greater than the cooling energy requirement. Gas-fired cooling systems, in the Large Office Building, were expected to show significantly greater economic attractiveness than in the Medium Building. The results presented in Tables 2 (b) and 3 (b) and in Figures 3 and 5 supported that premise.

Unlike the case in the Medium Building, the air-side economizer is a must in the Large Building. Without the air-side economizer (System 1 (a)), total annual operating costs increase in Tables 2 (b) and 3 (b). System 1 was therefore picked as the base case electric cooling system for subsequent comparisons with gas-fired Systems 2, 3 and 3 (a).

The highest operating cost reduction was with the double-effect absorption chillers (System 2), in the City of Toronto, while a combination plant (System 3 (a)) achieved the greatest operating cost reduction in the City of North York. Winter billing peak demand reductions were about 30 kW, for Systems 2 and 3. System 2 reduced the summer billing peak demand by over 700 kW; System 3 by 435 kW.

Combination Plants

As in the Medium Office Building, two combination, gas-fired/electric cooling plants were simulated. As before, one plant had gas-fired cooling base load (System 3), while the other assumed electric chiller base loading. Unlike the Medium Office Building, where the same combination system (gas-fired base load) was the more attractive, in both cities, in the Large Office Building, the more attractive combination system changes with changing electrical rate structure (i.e. city).

In North York, with the more favourable electricity to gas price ratio, it does not make sense to use the relatively inefficient double-effect absorption cooling (COP-1), as base load, when a centrifugal chiller, with a much higher efficiency (COP=5.4), is available. Electric chiller base loading, System 3 (a), reduces heating and cooling energy costs by $12,000 compared to the gas-fired absorption (System 3) base loaded system, more than offsetting the $6500 annual billing demand cost reduction attributed to the gas base-loaded combination plant (System 3).

In the City of Toronto, there is a dramatic turn-around in the fortunes of the two combination systems. Because of a much higher electricity to natural gas price ratio, in the City of Toronto, the electric centrifugal chiller's superior operating efficiency yields insignificant heating and cooling energy cost reductions (less than $25). A billing demand cost reduction in excess of $8,500, allows the gas-fired absorption chiller to become the more attractive combination cooling plant in the City of Toronto.

Economic Attractiveness

In Figure 3, the simple payback period for the gas-fired systems, in the City of Toronto, is presented. In all three cases examined, the payback period is less than 7 years. The gas-fired base load, combination plant, shows a payback period of less than 4 years; while the electric centrifugal chiller base loaded combination plant has a simple payback period of about 6 years.

Impact of Incentives

All systems reduce peak billing electrical demand sufficiently to qualify for a "Savings by Design" 50 percent incremental capital cost incentive. These incentives would range from about $50,000, for a combination plant, to over $130,000 for a complete gas-fired absorption plant, lowering simple payback periods to between 2 and 3.5 years, as shown in Figure 3.

In the City of North York, the electric chiller base-loaded, combination plant has a simple payback period of about 13 years, as shown in Figure 5. This system could qualify for the "Savings by Design", 50 percent incremental capital cost incentive, as it reduces peak billing electrical demand, by more than 1000 kW. With the incentive applied, the simple payback period would be about six years. If the gas utility provided a further incentive of about $25 per ton, the simple payback period would be two years.

3.1.3 RESIDENTIAL SINGLE-FAMILY HOUSE

The Residential Single-Family house was assumed to have a design heating requirement of about 15 kW in a Toronto location. A design cooling load of 3 tons was also assumed. Both a gas engine-driven heat pump and a state-of-the-art electric heat pump were evaluated for a complete heating season. A bin method of energy analysis was used as the DOE 2.1D program cannot model engine-driven heat pumps.

The performance specification for the engine-driven heat pump was provided by the Gas Research Institute. The performance specifications for the electric heat pump were based on a manufacturers' catalog ratings.

Performance Comparison

Tables 4(a), 4(b) and 4(c) present the results for an all-electric heat pump, and add-on electric heat pump to a gas furnace and the engine-driven heat pump, respectively. The heating load, heating energy requirement, heat pump capacity and input, auxiliary heating requirement, and system energy use are tabulated as a function of outdoor temperature. The over-all performance of each system is provided at the bottom right-hand corner of each table.

The all-electric heat pump, in Table 4(a), has a seasonal coefficient of performance of 1.83 including the supplementary or auxiliary resistance heating energy. This represents a 45 percent reduction in heating energy compared to electric resistance heating of the same house. However, given the current cost of electricity, 6 cents per kWh, the heating cost with this system, in the Toronto location, is $1139. This system had the highest operating cost of the three examined.

Table 4(b) presents the performance of an add-on heat pump to a gas furnace in the same house. Unlike the all-electric heat pump, one cannot readily calculate the seasonal coefficient of performance for a dual-fuel system. The heat pump, by itself, has a coefficient of performance, over the year, of 2.42. The back-up gas furnace is assumed to have a seasonal efficiency of 65%. The over-all operating cost is about $200 lower than that of the all-electric heat pump in Table 4(a).

The gas engine heat-pump shown in Table 4(c) has the lowest over-all operating cost, including the electrical energy for fans and controls. The operating cost reduction with the gas engine-driven heat pump compared to the add-on heat pump system is about $225. This is largely due to the high electricity to natural gas price ratio which is 3 to 1. The C.O.P. ratio favours the electric heat pump by about 2 to 1, but not sufficient to overcome the significant fuel cost difference. Their relative operating costs are further widened because the average unit cost of the natural gas used to back-up the electric heat pump is about 12 percent more expensive than that used by the gas engine-driven heat pump. The gas engine-driven heat pump obviously represents a more favourable load to the gas utility than the add-on heat pump.

The cooling performance of the three systems has not been evaluated by the bin method of energy analysis. The electric heat pump used in the evaluations has a Seasonal Energy Efficiency Ratio (SEER) of 10.1. The GRI gas engine-driven heat pump does not have a certified SEER rating. Literature published by GRI claims a seasonal gas cooling C.O.P. of 1.26, which does not include electricity used by the indoor and outdoor fan motors. It can therefore be concluded that the SEER would be approximately 4, which would suggest operating costs in cooling, comparable to the electric heat pump.

Economic Attractiveness

GRI state that the target installed cost of the York gas engine heat pump is approximately $4500 U.S. One can estimate the cost/benefit, as follows. An incremental installed cost of $1000 would suggest a simple payback period of about 4.5 years compared to an electric add-on heat pump. If the incremental installed cost is $2000, the simple payback period would rise to 9 years.

4. CONCLUSIONS

Natural gas-fired cooling equipment is most attractive economically in large office buildings, characterized as having cooling loads in excess of annual heating loads, and where, the electrical demand peaks are due to electric cooling equipment operation.

Natural gas-fired cooling plants are most attractive in locales where the electricity to gas price ratio is high, particularly locales, such as the City of Toronto, where the electric rates structure discourages high billing demand, by punitive energy charges tied to billing demand.

Combination gas/electric cooling plants show more favourable payback periods than total gas-fired cooling plants. These plants have lower capital costs and, more importantly, the majority of cooling loads can be met with much less than design cooling capacity.

In the combination plant, the decision as to which plant is base-loaded depends on the gas/electricity price ratio and the relative cooling efficiencies of the gas and electric cooling equipment. For a given electricity/gas price ratio, the higher the electric to gas-fired cooling equipment efficiency ratio, the more attractive electric base-loading appears. For the examples here, the efficiency ratio in the Large Building was 5.4; in the Medium Building 3.2.

The addition of heat recovery, for the engine-driven chiller case presented here, would appear to be an attractive option, improving the over-all economic benefit of the system, in the Medium Office Building.

Existing electric utility demand management program incentives could result in payback periods under five years for the more promising gas-fired cooling systems examined. In the Medium Office Building, a supplementary gas utility incentive of $25 per ton would be required to lower the simple payback period, for the most promising system, to two years.

The small gas engine heat pump under development at York International, with GRI support, promises to reduce heating operating costs compared to electric add-on heat pumps by about 25 percent. If GRI installed cost targets for this unit are met, simple payback periods of 5 years are predicted. This assumes that service and maintenance costs for the two competing technologies are comparable.

5. RECOMMENDATIONS

A subsequent phase of this project should undertake additional computer simulations to quantify and better understand/identify additional opportunities for natural gas-fired cooling technologies. Consider the following:

(i) The two office buildings analyzed here were at opposite ends of the spectrum. One had an annual cooling load in excess of heating load by 40 percent; the other had a heating load 40 percent in excess of annual cooling load. There are a large range of office buildings between these two extremes and the importance of the annual cooling to heating load ratio could be better determined by an additional building simulation where, for example, the annual cooling load was approximately equal to the annual heating load.

(ii) Other buildings in the commercial/institutional sector may offer more or equally attractive opportunities for gas-fired cooling systems. Other buildings characterized by electricity peaks due to electric cooling, such as hotels, need to be investigated. Buildings, other than offices, with coincident demands for heating and cooling, such as hospitals, should be investigated for applications of the engine-driven chiller with heat recovery.

(iii) Combination plants are particularly attractive applications. Only plants with equal electric and gas-fired capacity components (i.e. 50/50) have been examined. There is a need to examine the effect of plant capacity split, (i.e. 20/80, 40/60, 60/40, 80/20) and how electricity to gas price ratio and gas-fired/electric cooling efficiency ratios impact on the economic attractiveness. An optimum capacity split is likely to exist for given fuel prices and competing system cooling efficiencies.

(iv) Two additional gas/fired cooling systems remain to be investigated. A gas-fired, desiccant cooling roof-top unit and the engine-driven roof-top unit currently offered by Thermo-King are available but have not yet been evaluated. The latter would be particularly attractive because the competing electric air-cooled, roof-top equipment has relatively low efficiency.

(v) Thermal Cool Storage is another area where electric utility incentive programs apply. The costs/benefits of combination plants should be compared to that of thermal cool storage, with electric cooling systems. The use of natural gas to avoid electricity use on peak may be more attractive offering lower cost to both the electric utility and the customer, than thermal cool storage.

(vi) The relative performance of the gas engine heat pump and the electric add-on heat pump should be evaluated in other locales with different fuel and electricity prices and climate.

6. REFERENCES

1. Pietsch, P.E. 1988. "Water-Loop Heat Pump Systems: "Assessment Study." Electric Power Research Institute, report PRI EM-5437.

2. R.S. Means Company, Inc. 1990. "Means Mechanical Cost Data, 1991"., 14th Annual Edition."

3. Arthur D. Little Inc. 1989. "Assessment of Large Tonnage Gas-Fired Cooling Technologies for the Commercial Sector."

Description of Building

Total Floor Area	49,000 ft2
Number of Floors	3
Maximum Occupancy	487 persons
Occupancy Hours	8:30-18:30
Off days	Weekends, Holidays
Lighting Levels	2.0 W/ft2
Electrical Equipment	0.45 W/ft2

Design Conditions and Loads

Design Cooling Load	85 tons
Design Heating Load	1800 kBTU/h
Annual Cooling Energy	225 MWh
Annual Heating Energy	315 MWh

Figure 1a Medium Office Building Characteristics

Description of Building

Total Floor Area	620,000 ft2
Number of Floors	31
Maximum Occupancy	4836 persons
Occupancy Hours	8:30-17:30
Off days	Weekends, Holidays
Lighting Levels	2.0 W/ft2
Electrical Equipment	0.2 W/ft2

Design Conditions and Loads

Design Cooling Load	1325 tons
Design Heating Load	20300 kBTU/h
Annual Cooling Energy	2550 MWh
Annual Heating Energy	850 MWh

Figure 1b Large Office Building Characteristics

Table 1(a) Incremental Capital Cost Gas-Fired Cooling Plants - Medium Office Building

System #	System Description	Estimated Incremental Capital Cost ($)
1	1-84 ton, electric reciprocating chiller	-
2	1-84 ton, engine-driven chiller	40200
3	1-84 ton, engine-driven chiller, with heat recovery option	48900
4	2-42 ton, electric reciprocating chillers	9900
5	2-42 ton, engine-driven chillers	59900
6	1-42 ton, electric chiller, 1-42 ton, engine-driven chiller - combination plant	34700

Table 1(b) Incremental Capital Cost Gas-Fired Cooling Plants - Large Office Building

System #	System Description	Estimated Incremental Capital Cost ($)
1	2-675 ton, electric centrifugal chillers	-
2	2-675 ton, double-effect absorption chillers	266500
3	1-675 ton, electric chiller, 1-675 ton, absorption chiller - combination plant	100900

1990 Toronto Hydro Rate Schedule

Monthly Demand Charge:	*$5.11 per kW of billing demand*	
Energy Charge:	*First 100 kWh/kW*	$0.1111/kWh
	Next 100 kWh/kW	$0.0509/kWh
	Balance	$0.0352/kWh

1990 North York Hydro Rate Schedule

Monthly Demand Charge:	*First 50 kW*	No Charge
	Next 4950 kW	$3.90/kW
	Balance	$10.77/kW
Energy Charge:	*First 250 kWh*	$0.0870/kWh
	Next 12250 kWh	$0.0628/kWh
	Next 1680000 kWh	$0.0471/kWh
	Balance	$0.0268/kWh

1990 Consumers' Gas General Service

	Dec to Mar	Apr to Nov
Monthly Charge:	$8.00	$8.00
Delivery Charge (cents):		
First 30 m3 per month	5.80	4.80
Next 55 m3 per month	5.19	4.19
Next 1315 m3 per month	4.68	3.68
Next 1400 m3 per month	4.33	3.33
Next 2800 m3 per month	4.08	3.08
Next 5600 m3 per month	3.88	2.88
Supply Charge per m3 (cents):	11.9021	11.2741

Figure 2 Utility Rate Schedules

Table 2(a) HVAC Plant and System Energy Use, Electrical Demand and Operating Cost Reductions

Medium Office Building-North York

System #	System Description	Heating and Cooling Energy		Billing Peak Demand		Heating and Cooling Energy Cost Reduction ($)	Total Annual Electrical Demand Reduction (kW)	Billing Demand Cost Reduction ($)	Total Operating Cost Reduction ($)
		(kWh)	(m3)	Winter (kW)	Summer (kW)				
1	1-84 ton, electric reciprocating chiller	239927	51908	206	251	-	-	-	-
1a	1-84 ton, electric reciprocating chiller , w/o economizer	280103	34303	193	251	740	-8	-32	708
2	1-84 ton, engine-driven chiller	189839	66220	206	201	278	228	891	1169
2a	1-84 ton, engine-driven chiller, w/o economizer	209924	56180	192	194	814	311	1214	2028
3	1-84 ton, engine-driven chiller, w/ heat recovery	188693	64101	206	200	704	234	912	1616
3a	1-84 ton, engine-driven chiller, w/ heat recovery , w/o economizer	206630	49994	192	194	2008	312	1218	3226
4	2-42 ton, electric reciprocating chiller	233268	51908	206	251	314	15	58	372
5	2-42 ton, engine-driven chiller	182142	66332	206	195	624	284	1107	1731
6	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (electric base load)	223781	53927	206	219	460	147	573	1033
6a	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (gas base load)	189279	65353	206	215	428	216	844	1272

Note : Total Operating Cost Reduction = Heating & Cooling Energy Cost Reduction + Billing Demand Cost Reduction

Table 2(b) HVAC Plant and System Energy Use, Electrical Demand and Operating Cost Reductions

Large Office Building - North York

System #	System Description	Heating and Cooling Energy		Billing Peak Demand		Heating and Cooling Energy Cost Reduction ($)	Total Annual Electrical Demand Reduction (kW)	Billing Demand Cost Reduction ($)	Total Operating Cost Reduction ($)
		(kWh)	(m3)	Winter (kW)	Summer (kW)				
1	2-675 ton, electric centrifugal chillers	2299592	126279	1873	2540	-	-	-	-
1a	2-675 ton, electric centrifugal chillers , w/o economizer	2407790	126256	1873	2541	-5061	-186	-724	-5785
2	2-675 ton, double-effect absorption chillers	1892627	319230	1845	1832	-8500	3556	13869	5369
2a	2-675 ton, double-effect absorption chillers , w/o economizer	1926873	362695	1845	1832	-16233	3462	13501	-2732
3	1-675 ton, electric + 1-675 ton, absorption (gas base load)	1934619	305815	1845	2105	-8560	2689	10485	1925
3a	1-675 ton, electric + 1-675 ton, absorption (electric base load)	2219329	127464	1860	2206	3464	1008	3933	7397

Note : Total Operating Cost Reduction = Heating & Cooling Energy Cost Reduction + Billing Demand Cost Reduction

Table 3(a) HVAC Plant and System Energy Use, Electrical Demand and Operating Cost Reductions

Medium Office Building - City of Toronto

System #	System Description	Heating and Cooling Energy (kWh)	Heating and Cooling Energy (m3)	Billing Peak Demand Winter (kW)	Billing Peak Demand Summer (kW)	Heating and Cooling Energy Cost Reduction ($)	Total Annual Electrical Demand Reduction (kW)	Billing Demand Cost Reduction ($)	Total Operating Cost Reduction ($)
1	1-84 ton, electric reciprocating chiller	239927	51908	206	251	-	-	-	-
1a	1-84 ton, electric reciprocating chiller , w/o economizer	280103	34303	193	251	1143	-8	-42	1101
2	1-84 ton, engine-driven chiller	189839	66220	206	201	1775	228	1168	2943
2a	1-84 ton, engine-driven chiller, w/o economizer	209924	56180	192	194	3309	311	1591	4900
3	1-84 ton, engine-driven chiller, w/ heat recovery	188693	64101	206	200	2238	234	1196	3434
3a	1-84 ton, engine-driven chiller, w/ heat recovery , w/o economizer	206630	49994	192	194	4474	312	1596	6070
4	2-42 ton, electric reciprocating chiller	233268	51908	206	251	372	15	77	449
5	2-42 ton, engine-driven chiller	182142	66332	206	195	2536	284	1450	3986
6	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (electric base load)	223781	53927	206	219	1614	147	751	2365
6a	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (gas base load)	189279	65353	206	215	1809	216	1106	2915

Note : Total Operating Cost Reduction = Heating & Cooling Energy Cost Reduction + Billing Demand Cost Reduction

Table 3(b) HVAC Plant and System Energy Use, Electrical Demand and Operating Cost Reductions
Large Office Building - City of Toronto

System #	System Description	Heating and Cooling Energy		Billing Peak Demand		Heating and Cooling Energy Cost Reduction ($)	Total Annual Electrical Demand Reduction (kW)	Billing Demand Cost Reduction ($)	Total Operating Cost Reduction ($)
		(kWh)	(m3)	Winter (kW)	Summer (kW)				
1	2-675 ton, electric centrifugal chillers	2299592	126279	1873	2540	-	-	-	-
1a	2-675 ton, electric centrifugal chillers , w/o economizer	2407790	126256	1873	2541	-5481	-186	-948	-6429
2	2-675 ton, double-effect absorption chillers	1892627	319230	1845	1832	19230	3556	18170	37400
2a	2-675 ton, double-effect absorption chillers , w/o economizer	1926873	362695	1845	1832	11036	3462	17690	28726
3	1-675 ton, electric + 1-675 ton, absorption (gas base load)	1934619	305815	1845	2105	11717	2689	13738	25455
3a	1-675 ton, electric + 1-675 ton, absorption (electric base load)	2219329	127464	1860	2206	11738	1008	5153	16891

Note : Total Operating Cost Reduction = Heating & Cooling Energy Cost Reduction + Billing Demand Cost Reduction

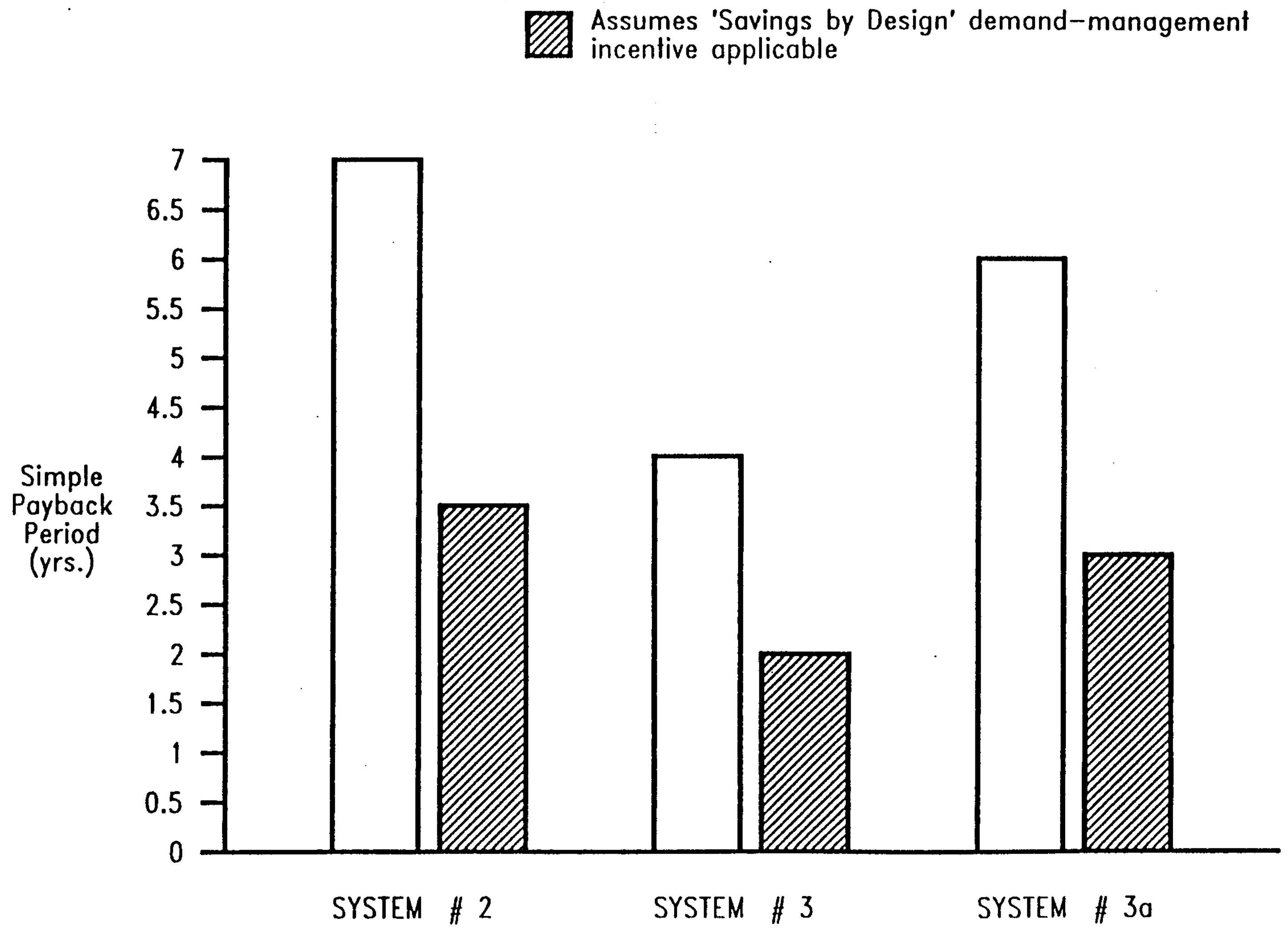

Figure 3 Economic Attractiveness of Gas-Cooling – Large Office Building – City of Toronto

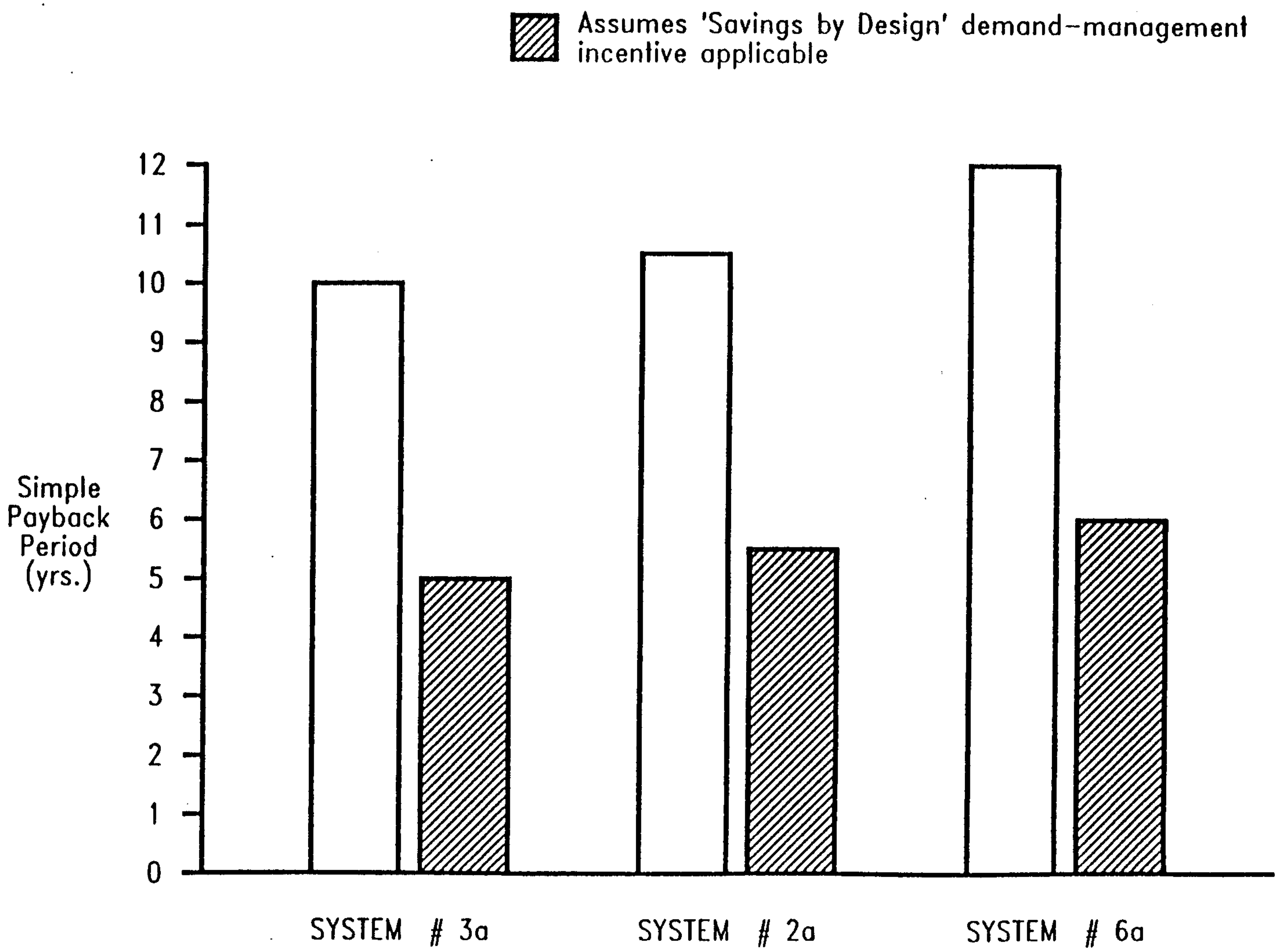

Figure 4 Economic Attractiveness of Gas-Cooling - Medium Office Building - City of Toronto

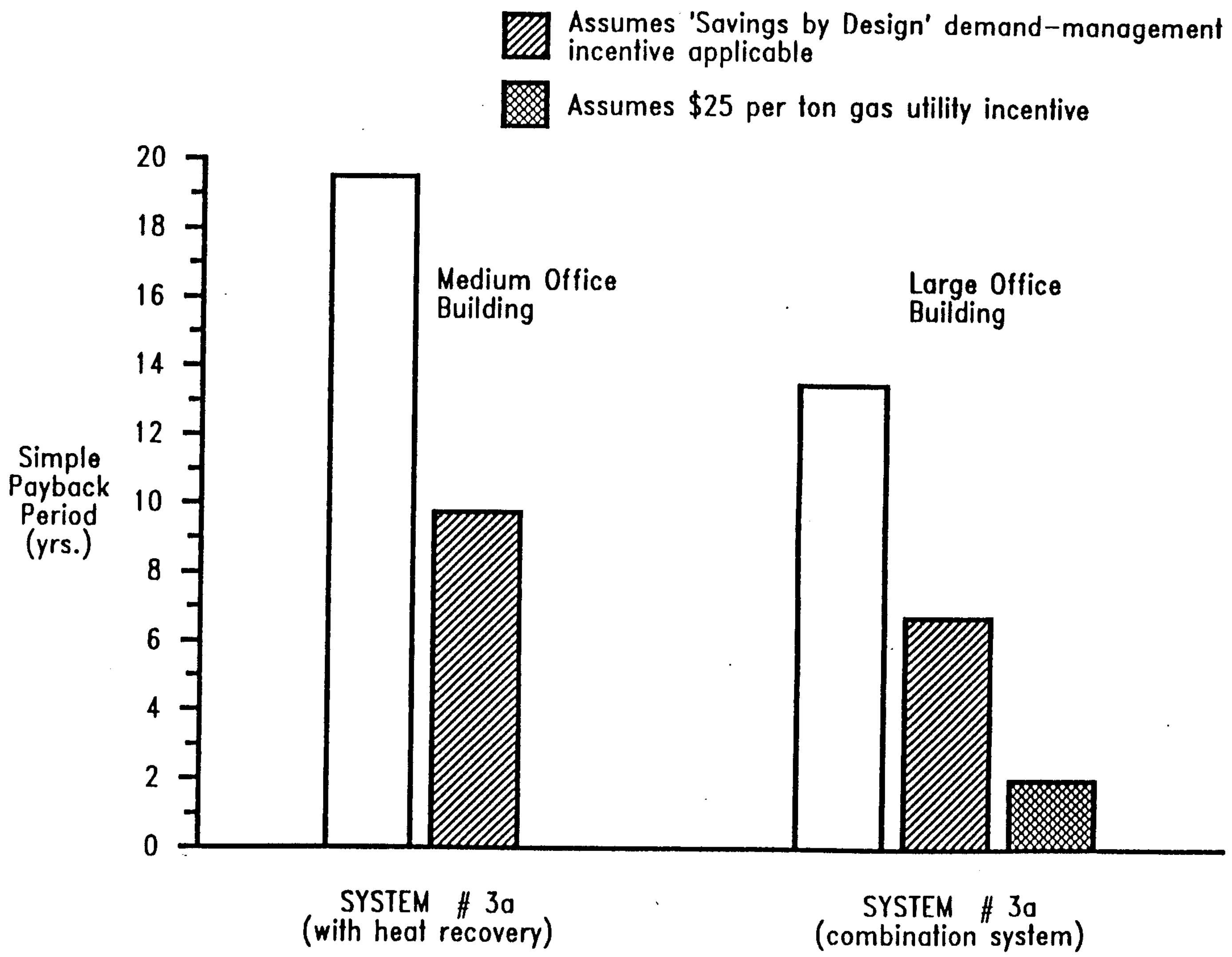

Figure 5 Economic Attractiveness of Gas-Cooling – City of North York

Table 4(a) System Energy Use and Operating Cost - All-Electric Heat Pump - Toronto

AUX. EFFICIENCY : (%) 100

O.D.T.	HEATING SEASON	HEATING LOAD	HEATING ENERGY REQ'D	HEATING CAPACITY	HEATING AUX. REQ'D	HP INPUT	AUX. INPUT REQ'D	ELEC. ENERGY FOR HP	ELEC. ENERGY FOR AUX.
F	hours	kW	kWh	kW	kW	kW	kW	kWh	kWh
70	0	0.000	0	16.508	0.000	3.992	0.000	0	0
65	0	0.000	0	15.136	0.000	3.874	0.000	0	0
60	0	0.000	0	13.842	0.000	3.759	0.000	0	0
55	360	0.993	358	12.625	0.000	3.647	0.000	103	0
50	448	2.235	1001	11.487	0.000	3.538	0.000	308	0
45	544	3.476	1891	10.426	0.000	3.432	0.000	622	0
40	651	4.718	3071	9.443	0.000	3.329	0.000	1083	0
35	804	5.959	4791	8.538	0.000	3.229	0.000	1812	0
30	757	7.201	5451	7.710	0.000	3.132	0.000	2214	0
25	548	8.442	4626	6.960	1.482	3.038	1.482	1665	812
20	417	9.684	4038	6.289	3.395	2.947	3.395	1229	1416
15	314	10.925	3431	5.694	5.231	2.859	5.231	898	1643
10	220	12.167	2677	5.178	6.989	2.774	6.989	610	1538
5	137	13.408	1837	4.740	8.669	2.692	8.669	369	1188
0	75	14.650	1099	4.379	10.271	2.613	10.271	196	770
-5	36	15.891	572	4.096	11.796	2.537	11.796	91	425
-10	16	17.133	274	3.891	13.242	2.464	13.242	39	212
TOTAL	5311		34843					11201	7791

SYSTEM SEASONAL COP : 1.83

	HP	AUX.	
ENERGY COSTS :	0.06	0.06	$/unit fuel

PURCHASED HP ENERGY : 672 $

PURCHASED AUX. ENERGY : 467 $

TOTAL SYSTEM ENERGY COST : 1139 $

Table 4(b) System Energy Use and Operating Cost - Add-on Electric Heat Pump to Gas Furnace - Toronto

AUX. EFFICIENCY : (%) 65

O.D.T.	HEATING SEASON	HEATING LOAD	HEATING ENERGY REQ'D	HEATING CAPACITY	HEATING AUX. REQ'D	HEATING AUX. ENERGY	HP INPUT	AUX. INPUT REQ'D	ELEC. ENERGY FOR HP	GAS ENERGY FOR AUX.
F	hours	kW	kWh	kW	kW	kWh	kW	kW	kWh	m3
70	0	0.000	0	16.508	0.000	0	3.992	0.000	0	0
65	0	0.000	0	15.136	0.000	0	3.874	0.000	0	0
60	0	0.000	0	13.842	0.000	0	3.759	0.000	0	0
55	360	0.993	358	12.625	0.000	0	3.647	0.000	103	0
50	448	2.235	1001	11.487	0.000	0	3.538	0.000	308	0
45	544	3.476	1891	10.426	0.000	0	3.432	0.000	622	0
40	651	4.718	3071	9.443	0.000	0	3.329	0.000	1083	0
35	804	5.959	4791	8.538	0.000	0	3.229	0.000	1812	0
30	757	7.201	5451	7.710	0.000	0	3.132	0.000	2214	0
25	548	8.442	4626	6.960	1.482	812	3.038	2.280	1665	121
20	417	9.684	4038	6.289	3.395	1416	2.947	5.223	1229	211
15	314	10.925	3431	5.694	5.231	1643	2.859	8.048	898	244
10	220	12.167	2677	5.178	6.989	1538	2.774	10.752	610	229
5	137	13.408	1837	4.740	8.669	1188	2.692	13.337	369	177
0	75	14.650	1099	4.379	10.271	770	2.613	15.802	196	115
-5	36	15.891	572	4.096	11.796	425	2.537	18.147	91	63
-10	16	17.133	274	3.891	13.242	212	2.464	20.373	39	32
TOTAL	5311		34843			7791			11201	1158

HEAT PUMP ONLY COP : 2.42

	HP	AUX.	
ENERGY COSTS :	0.06	0.232	$/unit fuel

PURCHASED HP ENERGY : 672 $

PURCHASED AUX. ENERGY : 268 $

TOTAL SYSTEM ENERGY COST : 940 $

Table 4(c) System Energy Use and Operating Cost - Gas Engine-Driven Heat Pump - Toronto

AUX. EFFICIENCY : (%) 65

O.D.T.	HEATING SEASON	HEATING LOAD	HEATING ENERGY REQ'D	HEATING CAPACITY	HEATING AUX. REQ'D	HEATING AUX. ENERGY	INPUT GAS HP	INPUT FANS HP	INPUT AUX.	GAS ENERGY FOR HP	ELEC. ENERGY FOR HP	GAS ENERGY FOR AUX.
F	hours	kW	kWh	kW	kW	kWh	kW	kW	kW	m3	kWh	m3
70	0	0.000	0	8.832	0.000	0	5.012	0.430	0.000	0	0	0
65	0	0.000	0	8.273	0.000	0	4.894	0.430	0.000	0	0	0
60	0	0.000	0	7.737	0.000	0	4.774	0.430	0.000	0	0	0
55	360	0.993	358	7.222	0.000	0	4.651	0.430	0.000	22	21	0
50	448	2.235	1001	6.728	0.000	0	4.525	0.430	0.000	65	64	0
45	544	3.476	1891	6.257	0.000	0	4.397	0.430	0.000	128	130	0
40	651	4.718	3071	5.808	0.000	0	4.266	0.430	0.000	218	227	0
35	804	5.959	4791	9.142	0.000	0	6.814	0.430	0.000	345	225	0
30	757	7.201	5451	8.420	0.000	0	6.519	0.430	0.000	408	278	0
25	548	8.442	4626	11.445	0.000	0	9.260	0.430	0.000	362	174	0
20	417	9.684	4038	10.579	0.000	0	8.889	0.750	0.000	328	286	0
15	314	10.925	3431	9.736	1.189	373	8.518	0.750	1.830	258	236	56
10	220	12.167	2677	8.915	3.251	715	8.146	0.750	5.002	173	165	106
5	137	13.408	1837	8.118	5.291	725	7.773	0.750	8.140	103	103	108
0	75	14.650	1099	7.342	7.307	548	7.400	0.750	11.242	54	56	81
-5	36	15.891	572	6.590	9.302	335	7.026	0.750	14.310	24	27	50
-10	16	17.133	274	5.860	11.273	180	6.651	0.750	17.343	10	12	27
TOTAL	5311		34843			2696				2489	1993	401

HEAT PUMP ONLY COP : 1.16

	HP	AUX.	
ENERGY COSTS :	0.06	0.207	$/unit fuel

PURCHASED HP ENERGY : 635 $

PURCHASED AUX. ENERGY : 83 $

TOTAL SYSTEM ENERGY COST : 717 $

APPENDIX D

ENVIRONMENTAL IMPACT OF GAS COOLING TECHNOLOGIES

ENVIRONMENTAL IMPACT OF GAS COOLING TECHNOLOGIES

1. INTRODUCTION

In the current phase of this investigation, the environmental impact of gas cooling is compared to that of electric cooling. The systems employed in the previous interim report, entitled "Performance and Economic Attractiveness of Gas Cooling Compared to Electric Cooling in Canadian Buildings", are also used in this comparison. The simulated gas and electricity consumptions presented there and best estimates of refrigerant and methane leakage rates have been used to calculate the relative impacts of these systems, in terms of ozone depletion potential and global warming potential.

Ozone depletion potential has been quantified in terms of the equivalent mass of CFC-11 released annually and the global warming potential/greenhouse gas production is given by the equivalent mass of CO_2 produced annually.

2. METHOD

2.1 BUILDING AND COOLING SYSTEMS

The buildings and systems used in this assessment have been described in the "Performance and Economic Attractiveness" report (1). Systems 1,2, and 3 in the medium office building and Systems 1a and 2a in the large office building, that were all found to be unattractive, have been excluded from the environmental impact assessment.

2.2 REFRIGERANT EMISSIONS

As 45-50 percent of CFC usage in Canada is in HVAC and refrigeration applications, loss of refrigerant is usually an important consideration with respect to the "environmental friendliness" of cooling systems. The absorption and desiccant gas cooling technologies can have significant advantages in this regard because CFCs are not used as working fluids.

It is estimated (2) that in 1986 there were 110,000 centrifugal chillers in the world which released 17.3×10^6 lbs of refrigerant (90% CFC-11 or CFC-12) that year. This translates to emissions of about 11.7% of the refrigerant contained in the equipment or 12% if the releases related to manufacturing, shipping and installation are added in. As it is believed that reciprocating compressor systems should on average have leakage, service and disposal characteristics similar to the centrifugal equipment, the 12% per annum emission rate is assumed for all of the electric and gas-engine driven chillers studied as well.

The suppliers of the double-effect absorption system claim that their system must have zero leakage because a high vacuum is necessary for proper operation. The working fluid in this system is a lithium bromide and water mixture. LiBr is not known (4) to be an ozone destroying molecule and it has therefore been assumed to have an ozone depletion potential of zero. However, bromine alone is definitely known to react with ozone so the relative ozone depletion potential for LiBr is still being pursued. Ammonia, the most common working fluid in single-effect absorption cycles, has an ozone depletion potential of zero.

The equivalent mass of CFC-11 released by each system is simply the product of the system charge, the annual leakage rate and the relative ozone depletion potential for the refrigerant being used. Since the engine-driven chillers used in the medium office building simulation are essentially large chillers with reduced capacity achieved through lower speed operation, appropriate refrigerant charges had to be estimated. These charges were assumed to be equal to those used in the equivalent capacity electric systems. The large building systems were very close in capacity to off-the-shelf systems so that manufacturers data defined the refrigerant charge, in each case.

2.3 ELECTRICAL GENERATION MIX

While the gas and electrical energy used in the office buildings were determined through simulations using Toronto weather data, this environmental assessment uses two very different electrical generation mixes to supply electricity to the buildings. One is roughly consistent with the Toronto location, as it is the mix predicted by Ontario Hydro for 1993 (3); 15% of the electrical energy is produced in fossil-fuel-fired plants. The other, a worst-case for electrical-generated emissions, assumes that 100% of the electricity is fossil-generated. While this scenario is accurate for Prince Edward Island, most electrical energy is generated with fossil-fuels (4) in Alberta (96%), Saskatchewan (82%), Nova Scotia (87%) and New Brunswick (50.1%).

Since the generation mix varies with the electrical system load, and cooling system loads also vary with time, the exact generation mix appropriate for calculating emissions due to cooling system operation has not been determined. In Ontario, in 1993, the fossil component must be between 0 and 37% (fossil generation capacity) and is likely slightly greater than the 15% predicted average.

2.4 EMISSIONS FROM ELECTRICAL GENERATION

Atmospheric emissions of CO_2, SO_2, NO_x, particulates and the corresponding amounts of electricity generated, were obtained for Ontario Hydro fossil-fuel-fired thermal generating stations (5) for 1987, 1988 and 1989. Average emissions of each component per kWh generated were calculated for these stations, the predicted 1993 system generation mix and for the energy reaching the end user (accounting for transmission and distribution losses (4) of 7.7%).

The equivalent mass of CO_2 gas emitted was calculated for each electric cooling system considered by taking the product of the electrical energy consumed, the end use emission factor and the relative global warming potential for each component emitted. Particulates and SO_2 gas emissions are not considered to be significant in terms of greenhouse effect, but were retained in the spreadsheets because of their importance with regard to other environmental effects, such as acid rain. While NO_x is not considered to be a direct greenhouse gas, it has been included because of the importance of the indirect greenhouse effect of its reaction with tropospheric O_3.

2.5 ENGINE EMISSIONS

Tecogen Inc., the manufacturer of the engine driven chiller simulated in the medium office building, supplied data on NO_x and CO emissions for their 125 ton model, in terms of equivalent full load hours, with and without catalytic converter (6). Since the catalytic converter greatly reduces the output of NO_x (which has an indirect relative global warming potential of 150) it was assumed to be used in all cases. N_2O emissions were not reported but are generally believed (8) to be approximately three orders of magnitude smaller than NO_x emissions. As the global warming potential is roughly double that of NO_x the impact of N_2O should be roughly 500 times smaller and is ignored here.

The Tecogen data was supplemented with information from two other sources. Emissions of hydrocarbons and soot were estimated from data given by Meal (7) and CO_2 was estimated from a knowledge of the quantity of carbon in the fuel burned and the previously referred to emissions of CO and HC. The resulting factors, in terms of emission per unit of natural gas consumed were multiplied by the fuel used and the relative global warming potential factor to give the equivalent mass of CO_2 released.

2.6 BURNER EMISSIONS

Emissions from the natural gas burner in the absorption chiller and all other gas fired heating units were assumed to be the same: CO and HC emissions were derived from Meal (7) while CO_2 and NO_x[1] were taken from Coombs (8). Calculation of the equivalent mass of CO_2 released followed the same procedure as for engine emissions.

2.7 METHANE EMISSIONS

Methane emissions amounting to 0.3 to 0.36% of consumption have been estimated by the Canadian Gas Association for the production, transmission and distribution of natural

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[1] NO_x emissions were given by both references (9) and (8) as 41.8 g/GJ input and approximately 50 g/GJ input, respectively.

gas (8).

The equivalent mass of CO_2 released is calculated as the product of the quantity of gas consumed, the leakage factor (taken as 0.33%) and the relative global warming potential factor of 63 for methane.

The relative global warming potential factors are also applied to the mass of leaked refrigerant to determine this component in the total equivalent mass of CO_2 released.

3. RESULTS AND DISCUSSION

The atmospheric emissions for each system are summarized in Tables 1 and 2 and detailed in Appendices A and B, for 15% and 100% fossil-fuel generated electricity, respectively.

3.1 ELECTRICAL GENERATION MIX: 15% FOSSIL FUEL

The relative environmental impact of systems, using electricity that is 15% fossil-generated and 85% hydro and nuclear generated, is presented in this section.

3.1.1 MEDIUM OFFICE BUILDING

In the medium office building, the use of R22 in the cooling systems limits the impact of refrigerant release. There is little to choose between the systems with respect to potential ozone layer damage but the two-chiller systems are expected to release approximately 15% more refrigerant than their single chiller counterparts.

Greenhouse gas emissions, for this electrical generation mix are lowest for the all-electric chillers, Systems 1a and 4.

3.1.2 LARGE OFFICE BUILDING

In the large office building, there is great benefit in employing gas-fired cooling systems which use non ozone-depleting working fluids. The conventional all-electric cooling system (#1), is on average, expected to release into the atmosphere, approximately 140 kg of CFC-11 each year that it is in operation. The gas-only absorption system (#2) is expected to release no known ozone damaging material. The 50/50 combined gas-electric cooling systems (#3 and #3a) are predicted to release half as much refrigerant as the conventional system.

Greenhouse gas emissions are also predicted to be lower (by 21%) for System 2 (gas-only cooling), than for the conventional System 1 (all-electric cooling). When equal capacity gas and electric chillers are used in combination, even lower (by 5%) greenhouse gas emissions are produced by System 3a, in which the base load is carried by the electric chiller. The reason for this apparent reversal in greenhouse gas emissions is due to the loss, by the gas system , of its advantage with regard to refrigerant leakage.

3.2 ELECTRICAL GENERATION MIX: 100% FOSSIL FUEL

The relative environmental impact of systems, using electricity that is 100% fossil-generated, is presented in this section. Since the system by system release of ozone-damaging emissions, as presented in section 3.1, is unaffected by the electrical generation mix, only the greenhouse gas related emissions are treated in this section.

3.2.1 MEDIUM OFFICE BUILDING

Operation of the medium office building in a region where all electricity is fossil generated, results in a number of interesting developments. The overall effective emissions of greenhouse gasses roughly doubles relative to the 15% fossil-generated electricity case. The spread between the best and worst (in terms of greenhouse gas production) systems is reduced from 47% to only 7.5%. System 6, a combined gas/electric cooling system, with the electric chiller carrying the base load, produced the lowest greenhouse gas emissions. System 6a, an identical twin chiller system with gas carrying the base cooling load produced only 3 percent more greenhouse gas. Similarly System 5, with twin, engine-driven chillers, produced 2 percent more greenhouse gas than the corresponding twin electric chillers in System 4.

For such small differences in emissions, of both ozone-depleting and greenhouse gasses, it would be appropriate to use factors other than these in the selection of the most appropriate system.

3.2.2 LARGE OFFICE BUILDING

In the large office building, System 2, the all-gas cooling system is the most attractive from an environmental standpoint, from both ozone depletion and global warming perspectives. Second most attractive, is System 3a, the combined gas-electric cooling system with the electric chiller meeting the base load.

4. CONCLUSIONS

Natural gas-fired cooling equipment can be environmentally attractive both in terms of reduced ozone depletion potential and lower overall greenhouse gas emissions, in certain circumstances.

Gas cooling is most attractive from an environmental point of view, in regions where a high percentage of the electricity is produced by fossil-fuel fired generation.

Gas cooling equipment may also be attractive environmentally whenever the technology chosen employs a non ozone-depleting working fluid.

For 100% fossil-fuel generated electricity, the gas-only absorption cooling system is the most attractive large office building system examined, from both ozone depletion and greenhouse gas production points of view.

For 15% fossil generated electricity, the same gas-only system was most attractive from and ozone depletion perspective by the combined gas-electric cooling system (with the electric chiller meeting the bas load) proved most attractive regarding greenhouse gas production.

In the medium office building, there is not a significant difference between the gas engine and electrical driven chiller systems when electricity is 100% fossil generated, but the electric cooling systems are most attractive when electricity is 15% fossil generated.

5. RECOMMENDATIONS

Gas-fired cooling appears to be environmentally attractive relative to conventional electrical cooling under certain conditions. Examination of additional systems and electric generation mixes would allow better definition of the conditions under which the various technologies should, from and environmental perspective, be encouraged. Consider the following:

(i) Six chemical manufacturing companies including Allied, Dow, Dupont and Union Carbide have been contacted, along with Environment Canada, to obtain definitive information to confirm that the lithium bromide water solution used in double-effect absorption cycles (and some desiccant cooling technologies) is in fact, not a threat to ozone or an effective infrared absorber (greenhouse gas). Such information, has not yet been identified by any of the groups contacted.

(ii) Engine driven chillers were assumed to employ the same refrigerant charge as their electrically powered counterparts. It should be determined whether or not this is a correct assumption. Tecogen literature would suggest that refrigerant charges are larger than those of equivalent capacity conventional chillers.

(iii) Examination of the 15 and 100% fossil generated electricity cases shows that different systems are favoured depending on the generation mix. It would be useful to better define the range of generation mixes under which the gas technologies are environmentally beneficial.

6. REFERENCES

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5. Atmospheric Emissions from Ontario Hydro Fossil-Fuel-Fired Thermal Generating Stations, CTS-07120-2, 1987, 1988 & 1989.

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7. M. Meal, Air Pollutant Emission Comparison of Gas and Diesel Engine Driven Heat Pumps to Oil- and Gas-Fired Boilers, IEA Heat Pump Centre Newsletter, Vol.4, No.1, March 1986.

8. A. Coombs, Emission Factors for Greenhouse and other Gases by Fuel Type: An inventory, Ad Hoc Committee on Emission Factors, Energy, Mines and Resources, December 1990.

NOMENCLATURE FOR APPENDICES A AND B

Emitted Component	- the gas or particulate emitted by electrical generation, natural gas combustion, natural gas transmission, or refrigerant loss for the system under consideration.
Energy Consumed	- the electrical or gas energy consumed by the system under consideration.
Fossil Generation Emission Factor	- the mass of the gas or particulate emitted per kWh of electrical energy generated by fossil-fuel generation plants.
System Emission Factor	- the mass of the gas or particulate emitted per kWh of total generating system electrical energy produced, taking into account the generation mix.
Purchased Energy Factor	- the mass of the gas or particulate emitted per kWh of total system electrical energy consumed by the end user, taking into account generation mix and transmission and distribution losses.
Quantity of Emission	- the total mass of gas, particulate or refrigerant emitted per year for the system under consideration.
Global Warming	- a ratio equal to the global warming effect of a gas, integrated over a 20 year time horizon, divided by the global warming effect of the same mass of CO_2, over the same period. Multiplied by the mass of the gas or particulate it yields the equivalent mass of CO_2.
Combustion Emission Factor	- the mass of the gas or particulate emitted per m^3 of gas burned.
Leakage Factor	- the percentage of natural gas lost through production, transmission and distribution.
System Charge	- the mass of refrigerant in the system under consideration.
Loss Factor %/Year	- the percentage of the system charge assumed lost each year.
Ozone Depletion	- a ratio equal to the ozone depletion caused by a gas divided by the ozone depletion caused by the same mass of CFC-11. Multiplied by the refrigerant mass emitted it yields the

	equivalent mass of CFC-11.
Equivalent Mass of CO_2	- the mass of CO_2 that would have the same global warming effect as the emitted gas, over a 20 year period.
Equivalent Mass of CFC-11	- the mass of CFC-11 that would cause the same amount of ozone depletion as the emitted gas.

Table 1 Environmental Comparison of Systems
15% Fossil-Fuel Generated Electricity

#	System Description	Equivalent Mass of CO2 (kg)						Equivalent Mass of CFC-11 Total (kg)
		Electric Consumption	Gas Engine	Gas Burner	Gas Leakage	Refrigerant Loss	Total	
	Medium Office Building							
1a	1-84 ton, electric reciprocating chiller, w/o economizer	50,004	0	73,314	5,292	27,060	155,670	0.33
2a	1-84 ton, engine-driven chiller, w/o economizer	37,476	100,870	73,314	8,666	27,060	247,387	0.33
3a	1-84 ton, engine-driven chiller, w/ heat recovery, w/o economizer	36,888	100,806	60,123	7,712	27,060	232,589	0.33
4	2-42 ton, electric reciprocating chiller	41,643	0	110,941	8,007	31,488	192,079	0.38
5	2-42 ton, engine-driven chiller	32,516	66,511	110,941	10,232	31,488	251,688	0.38
6	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (electric base load)	39,950	9,314	110,941	8,319	31,488	200,011	0.38
6a	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (gas base load)	33,790	61,992	110,941	10,081	31,488	248,293	0.38
	Large Office Building							
1	2-675 ton, electric centrifugal chillers	410,526	0	269,891	19,480	650,700	1,350,597	144.60
2	2-675 ton, double-effect absorption chillers	337,874	0	682,277	49,245	0	1,069,396	0.00
3	1-675 ton, electric chiller + 1-675 ton, absorption chiller (gas base load)	345,370	0	653,606	47,176	325,080	1,371,231	72.24
3a	1-675 ton, electric chiller + 1-675 ton, absorption chiller (electric base load)	396,197	0	272,423	19,663	325,080	1,013,363	72.24

Table 2 Environmental Comparison of Systems
100% Fossil-Fuel Generated Electricity

#	System Description	Equivalent Mass of CO2 (kg)						Equivalent Mass of CFC-11 Total (kg)
		Electric Consumption	Gas Engine	Gas Burner	Gas Leakage	Refrigerant Loss	Total	
Medium Office Building								
1a	1-84 ton, electric reciprocating chiller, w/o economizer	333,362	0	73,314	5,292	27,060	**439,028**	**0.33**
2a	1-84 ton, engine-driven chiller, w/o economizer	249,839	100,870	73,314	8,666	27,060	**459,750**	**0.33**
3a	1-84 ton, engine-driven chiller, w/ heat recovery, w/o economizer	245,919	100,806	60,123	7,712	27,060	**441,620**	**0.33**
4	2-42 ton, electric reciprocating chiller	277,622	0	110,941	8,007	31,488	**428,058**	**0.38**
5	2-42 ton, engine-driven chiller	216,775	66,511	110,941	10,232	31,488	**435,947**	**0.38**
6	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (electric base load)	266,331	9,314	110,941	8,319	31,488	**426,392**	**0.38**
6a	1-42 ton, electric chiller + 1-42 ton, engine-driven chiller (gas base load)	225,269	61,992	110,941	10,081	31,488	**439,771**	**0.38**
Large Office Building								
1	2-675 ton, electric centrifugal chillers	2,736,838	0	269,891	19,480	650,700	**3,676,909**	144.60
2	2-675 ton, double-effect absorption chillers	2,252,493	0	682,277	49,245	0	**2,984,015**	0.00
3	1-675 ton, electric chiller + 1-675 ton, absorption chiller (gas base load)	2,302,469	0	653,606	47,176	325,080	**3,328,330**	72.24
3a	1-675 ton, electric chiller + 1-675 ton, absorption chiller (electric base load)	2,641,314	0	272,423	19,663	325,080	**3,258,480**	72.24

APPENDIX

Environmental Impact with 15% Fossil-Fuel Generation

Table A-1 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 1a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	280103	8.39 E-1	1.26 E-1	1.36 E-1	38191.7	1	38192
SO2	280103	8.88 E-3	1.33 E-3	1.44 E-3	404.2	0	0
NOx	280103	1.73 E-3	2.60 E-4	2.81 E-4	78.8	150	11813
Particulates	280103	2.77 E-4	4.16 E-5	4.50 E-5	12.6	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	34303	2.53 E-3			86.8	3	260
CO2	34303	1.87 E+0			64146.6	1	64147
NOx	34303	1.59 E-3			54.5	150	8181
HC	34303	7.56 E-4			25.9	28	726

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	34303	0.33			84.0	63	5292

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 155670 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table A-2 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 2a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	209924	8.39 E-1	1.26 E-1	1.36 E-1	28622.9	1	28623
SO2	209924	8.88 E-3	1.33 E-3	1.44 E-3	302.9	0	0
NOx	209924	1.73 E-3	2.60 E-4	2.81 E-4	59.0	150	8853
Particulates	209924	2.77 E-4	4.16 E-5	4.50 E-5	9.4	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	21877	1.92 E-2			420.0	3	1260
CO2	21877	1.86 E+0			40691.2	1	40691
NOx	21877	1.76 E-2			385.0	150	57755
HC	21877	1.90 E-3			41.6	28	1164
Soot	21877	3.80 E-5			0.8	0	0
Burner :							
CO	34303	2.53 E-3			86.8	3	260
CO2	34303	1.87 E+0			64146.6	1	64147
NOx	34303	1.59 E-3			54.5	150	8181
HC	34303	7.56 E-4			25.9	28	726

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	56180	0.33			137.6	63	8666

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 247387 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table A-3 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 3a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	206630	8.39 E-1	1.26 E-1	1.36 E-1	28173.8	1	28174
SO2	206630	8.88 E-3	1.33 E-3	1.44 E-3	298.2	0	0
NOx	206630	1.73 E-3	2.60 E-4	2.81 E-4	58.1	150	8714
Particulates	206630	2.77 E-4	4.16 E-5	4.50 E-5	9.3	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	21863	1.92 E-2			419.8	3	1259
CO2	21863	1.86 E+0			40665.2	1	40665
NOx	21863	1.76 E-2			384.8	150	57718
HC	21863	1.90 E-3			41.5	28	1163
Soot	21863	3.80 E-5			0.8	0	0
Burner :							
CO	28131	2.53 E-3			71.2	3	214
CO2	28131	1.87 E+0			52605.0	1	52605
NOx	28131	1.59 E-3			44.7	150	6709
HC	28131	7.56 E-4			21.3	28	595

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	49994	0.33			122.4	63	7712

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 232589 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table A-4 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 4

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	233268	8.39 E-1	1.26 E-1	1.36 E-1	31805.8	1	31806
SO2	233268	8.88 E-3	1.33 E-3	1.44 E-3	336.6	0	0
NOx	233268	1.73 E-3	2.60 E-4	2.81 E-4	65.6	150	9837
Particulates	233268	2.77 E-4	4.16 E-5	4.50 E-5	10.5	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	51908	0.33			127.1	63	8007

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 192079 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table A-5 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 5

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	182142	8.39 E-1	1.26 E-1	1.36 E-1	24834.9	1	24835
SO2	182142	8.88 E-3	1.33 E-3	1.44 E-3	262.9	0	0
NOx	182142	1.73 E-3	2.60 E-4	2.81 E-4	51.2	150	7681
Particulates	182142	2.77 E-4	4.16 E-5	4.50 E-5	8.2	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	14425	1.82 E-2			277.0	3	831
CO2	14425	1.86 E+0			26830.5	1	26831
NOx	14425	1.76 E-2			253.9	150	38082
HC	14425	1.90 E-3			27.4	28	767
Soot	14425	3.80 E-5			0.5	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	66332	0.33			162.4	63	10232

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 251688 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table A-6 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 6

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	223781	8.39 E-1	1.26 E-1	1.36 E-1	30512.3	1	30512
SO2	223781	8.88 E-3	1.33 E-3	1.44 E-3	322.9	0	0
NOx	223781	1.73 E-3	2.60 E-4	2.81 E-4	62.9	150	9437
Particulates	223781	2.77 E-4	4.16 E-5	4.50 E-5	10.1	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	2020	1.92 E-2			38.8	3	116
CO2	2020	1.86 E+0			3757.2	1	3757
NOx	2020	1.76 E-2			35.6	150	5333
HC	2020	1.90 E-3			3.8	28	107
Soot	2020	3.80 E-5			0.1	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	53927	0.33			132.0	63	8319

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LIBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 200011 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table A-7 Environmental Impact : 15% Fossil-Fuel Generation
Medium Office Building : System 6a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	189279	8.39 E-1	1.26 E-1	1.36 E-1	25808.0	1	25808
SO2	189279	8.88 E-3	1.33 E-3	1.44 E-3	273.2	0	0
NOx	189279	1.73 E-3	2.60 E-4	2.81 E-4	53.2	150	7982
Particulates	189279	2.77 E-4	4.16 E-5	4.50 E-5	8.5	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	13445	1.92 E-2			258.1	3	774
CO2	13445	1.86 E+0			25007.7	1	25008
NOx	13445	1.76 E-2			236.6	150	35495
HC	13445	1.90 E-3			25.5	28	715
Soot	13445	3.80 E-5			0.5	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	65353	0.33			160.0	63	10081

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 248293 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table A-8 Environmental Impact : 15% Fossil-Fuel Generation
Large Office Building : System 1

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	2299592	8.39 E-1	1.26 E-1	1.36 E-1	313546.8	1	313547
SO2	2299592	8.88 E-3	1.33 E-3	1.44 E-3	3318.6	0	0
NOx	2299592	1.73 E-3	2.60 E-4	2.81 E-4	646.5	150	96979
Particulates	2299592	2.77 E-4	4.16 E-5	4.50 E-5	103.5	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	126279	2.53 E-3			319.5	3	958
CO2	126279	1.87 E+0			236141.7	1	236142
NOx	126279	1.59 E-3			200.8	150	30118
HC	126279	7.56 E-4			95.5	28	2673

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	126279	0.33			309.2	63	19480

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	1205	12	23		144.6	4500	650700	1.00	144.60
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 1350597 kg

Annual Equivalent Mass of CFC-11 : 144.60 kg

Table A-9 Environmental Impact : 15% Fossil-Fuel Generation
Large Office Building : System 2

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	1892627	8.39 E-1	1.26 E-1	1.36 E-1	258057.5	1	258058
SO2	1892627	8.88 E-3	1.33 E-3	1.44 E-3	2731.3	0	0
NOx	1892627	1.73 E-3	2.60 E-4	2.81 E-4	532.1	150	79816
Particulates	1892627	2.77 E-4	4.16 E-5	4.50 E-5	85.2	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	319230	2.53 E-3			807.7	3	2423
CO2	319230	1.87 E+0			596960.1	1	596960
NOx	319230	1.59 E-3			507.6	150	76136
HC	319230	7.56 E-4			241.3	28	6757

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	319230	0.33			781.7	63	49245

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	15450	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 1069396 **kg**

Annual Equivalent Mass of CFC-11 : 0.00 **kg**

Table A-10 Environmental Impact : 15% Fossil-Fuel Generation
Large Office Building : System 3

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	1934619	8.39 E-1	1.26 E-1	1.36 E-1	263783.1	1	263783
SO2	1934619	8.88 E-3	1.33 E-3	1.44 E-3	2791.9	0	0
NOx	1934619	1.73 E-3	2.60 E-4	2.81 E-4	543.9	150	81587
Particulates	1934619	2.77 E-4	4.16 E-5	4.50 E-5	87.1	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	305815	2.53 E-3			773.7	3	2321
CO2	305815	1.87 E+0			571874.1	1	571874
NOx	305815	1.59 E-3			486.2	150	72937
HC	305815	7.56 E-4			231.2	28	6473

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	305815	0.33			748.8	63	47176

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	602	12	23		72.2	4500	325080	1.00	72.24
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	7725	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 1371231 kg

Annual Equivalent Mass of CFC-11 : 72.24 kg

Table A-11 Environmental Impact : 15% Fossil-Fuel Generation
Large Office Building : System 3a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	2219329	8.39 E-1	1.26 E-1	1.36 E-1	302603.0	1	302603
SO2	2219329	8.88 E-3	1.33 E-3	1.44 E-3	3202.8	0	0
NOx	2219329	1.73 E-3	2.60 E-4	2.81 E-4	624.0	150	93594
Particulates	2219329	2.77 E-4	4.16 E-5	4.50 E-5	99.9	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	127464	2.53 E-3			322.5	3	967
CO2	127464	1.87 E+0			238357.7	1	238358
NOx	127464	1.59 E-3			202.7	150	30400
HC	127464	7.56 E-4			96.4	28	2698

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	127464	0.33			312.1	63	19663

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	602	12	23		72.2	4500	325080	1.00	72.24
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	7725	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 1013363 kg

Annual Equivalent Mass of CFC-11 : 72.24 kg

APPENDIX

Environmental Impact
with
100% Fossil-Fuel Generation

Table B-1 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 1a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	280103	8.39 E-1	8.39 E-1	9.09 E-1	254611.5	1	254612
SO2	280103	8.88 E-3	8.88 E-3	9.62 E-3	2694.8	0	0
NOx	280103	1.73 E-3	1.73 E-3	1.87 E-3	525.0	150	78751
Particulates	280103	2.77 E-4	2.77 E-4	3.00 E-4	84.1	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	34303	2.53 E-3			86.8	3	260
CO2	34303	1.87 E+0			64146.6	1	64147
NOx	34303	1.59 E-3			54.5	150	8181
HC	34303	7.56 E-4			25.9	28	726

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	34303	0.33			84.0	63	5292

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 439028 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table B-2 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 2a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	209924	8.39 E-1	8.39 E-1	9.09 E-1	190819.3	1	190819
SO2	209924	8.88 E-3	8.88 E-3	9.62 E-3	2019.6	0	0
NOx	209924	1.73 E-3	1.73 E-3	1.87 E-3	393.5	150	59020
Particulates	209924	2.77 E-4	2.77 E-4	3.00 E-4	63.0	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	21877	1.92 E-2			420.0	3	1260
CO2	21877	1.86 E+0			40691.2	1	40691
NOx	21877	1.76 E-2			385.0	150	57755
HC	21877	1.90 E-3			41.6	28	1164
Soot	21877	3.80 E-5			0.8	0	0
Burner :							
CO	34303	2.53 E-3			86.8	3	260
CO2	34303	1.87 E+0			64146.6	1	64147
NOx	34303	1.59 E-3			54.5	150	8181
HC	34303	7.56 E-4			25.9	28	726

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	56180	0.33			137.6	63	8666

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 459750 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table B-3 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 3a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	206630	8.39 E-1	8.39 E-1	9.09 E-1	187825.1	1	187825
SO2	206630	8.88 E-3	8.88 E-3	9.62 E-3	1987.9	0	0
NOx	206630	1.73 E-3	1.73 E-3	1.87 E-3	387.3	150	58094
Particulates	206630	2.77 E-4	2.77 E-4	3.00 E-4	62.0	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	21863	1.92 E-2			419.8	3	1259
CO2	21863	1.86 E+0			40665.2	1	40665
NOx	21863	1.76 E-2			384.8	150	57718
HC	21863	1.90 E-3			41.5	28	1163
Soot	21863	3.80 E-5			0.8	0	0
Burner :							
CO	28131	2.53 E-3			71.2	3	214
CO2	28131	1.87 E+0			52605.0	1	52605
NOx	28131	1.59 E-3			44.7	150	6709
HC	28131	7.56 E-4			21.3	28	595

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	49994	0.33			122.4	63	7712

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	55	12	20		6.6	4100	27060	0.05	0.33
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 441620 kg

Annual Equivalent Mass of CFC-11 : 0.33 kg

Table B-4 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 4

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	233268	8.39 E-1	8.39 E-1	9.09 E-1	212038.8	1	212039
SO2	233268	8.88 E-3	8.88 E-3	9.62 E-3	2244.2	0	0
NOx	233268	1.73 E-3	1.73 E-3	1.87 E-3	437.2	150	65583
Particulates	233268	2.77 E-4	2.77 E-4	3.00 E-4	70.0	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	51908	0.33			127.1	63	8007

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 428058 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table B-5 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 5

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	182142	8.39 E-1	8.39 E-1	9.09 E-1	165565.7	1	165566
SO2	182142	8.88 E-3	8.88 E-3	9.62 E-3	1752.4	0	0
NOx	182142	1.73 E-3	1.73 E-3	1.87 E-3	341.4	150	51209
Particulates	182142	2.77 E-4	2.77 E-4	3.00 E-4	54.7	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	14425	1.92 E-2			277.0	3	831
CO2	14425	1.86 E+0			26830.5	1	26831
NOx	14425	1.76 E-2			253.9	150	38082
HC	14425	1.90 E-3			27.4	28	767
Soot	14425	3.80 E-5			0.5	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	66332	0.33			162.4	63	10232

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 435947 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table B-6 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 6

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	223781	8.39 E-1	8.39 E-1	9.09 E-1	203415.2	1	203415
SO2	223781	8.88 E-3	8.88 E-3	9.62 E-3	2153.0	0	0
NOx	223781	1.73 E-3	1.73 E-3	1.87 E-3	419.4	150	62916
Particulates	223781	2.77 E-4	2.77 E-4	3.00 E-4	67.2	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	2020	1.92 E-2			38.8	3	116
CO2	2020	1.86 E+0			3757.2	1	3757
NOx	2020	1.76 E-2			35.6	150	5333
HC	2020	1.90 E-3			3.8	28	107
Soot	2020	3.80 E-5			0.1	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	53927	0.33			132.0	63	8319

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 426392 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table B-7 Environmental Impact : 100% Fossil-Fuel Generation
Medium Office Building : System 6a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	189279	8.39 E-1	8.39 E-1	9.09 E-1	172053.2	1	172053
SO2	189279	8.88 E-3	8.88 E-3	9.62 E-3	1821.0	0	0
NOx	189279	1.73 E-3	1.73 E-3	1.87 E-3	354.8	150	53215
Particulates	189279	2.77 E-4	2.77 E-4	3.00 E-4	56.8	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	13445	1.92 E-2			258.1	3	774
CO2	13445	1.86 E+0			25007.7	1	25008
NOx	13445	1.76 E-2			236.6	150	35495
HC	13445	1.90 E-3			25.5	28	715
Soot	13445	3.80 E-5			0.5	0	0
Burner :							
CO	51908	2.53 E-3			131.3	3	394
CO2	51908	1.87 E+0			97068.0	1	97068
NOx	51908	1.59 E-3			82.5	150	12380
HC	51908	7.56 E-4			39.2	28	1099

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	65353	0.33			160.0	63	10081

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	64	12	20		7.7	4100	31488	0.05	0.38
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 439771 kg

Annual Equivalent Mass of CFC-11 : 0.38 kg

Table B-8 Environmental Impact : 100% Fossil-Fuel Generation
Large Office Building : System 1

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	2299592	8.39 E-1	8.39 E-1	9.09 E-1	2090311.7	1	2090312
SO2	2299592	8.88 E-3	8.88 E-3	9.62 E-3	22123.9	0	0
NOx	2299592	1.73 E-3	1.73 E-3	1.87 E-3	4310.2	150	646527
Particulates	2299592	2.77 E-4	2.77 E-4	3.00 E-4	690.1	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	126279	2.53 E-3			319.5	3	958
CO2	126279	1.87 E+0			236141.7	1	236142
NOx	126279	1.59 E-3			200.8	150	30118
HC	126279	7.56 E-4			95.5	28	2673

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	126279	0.33			309.2	63	19480

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	1205	12	23		144.6	4500	650700	1.00	144.60
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	-	-	-		-	0	-	0.00	-

Annual Equivalent Mass of CO2 : 3676909 kg

Annual Equivalent Mass of CFC-11 : 144.60 kg

Table B-9 Environmental Impact : 100% Fossil-Fuel Generation
Large Office Building : System 2

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	1892627	8.39 E-1	8.39 E-1	9.09 E-1	1720383.6	1	1720384
SO2	1892627	8.88 E-3	8.88 E-3	9.62 E-3	18208.6	0	0
NOx	1892627	1.73 E-3	1.73 E-3	1.87 E-3	3547.4	150	532109
Particulates	1892627	2.77 E-4	2.77 E-4	3.00 E-4	568.0	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	319230	2.53 E-3			807.7	3	2423
CO2	319230	1.87 E+0			596960.1	1	596960
NOx	319230	1.59 E-3			507.6	150	76136
HC	319230	7.56 E-4			241.3	28	6757

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	319230	0.33			781.7	63	49245

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	-	-	-		-	4500	-	1.00	-
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	15450	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 2984015 kg

Annual Equivalent Mass of CFC-11 : 0.00 kg

Table B-10 Environmental Impact : 100% Fossil-Fuel Generation
Large Office Building : System 3

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	1934619	8.39 E-1	8.39 E-1	9.09 E-1	1758554.0	1	1758554
SO2	1934619	8.88 E-3	8.88 E-3	9.62 E-3	18612.6	0	0
NOx	1934619	1.73 E-3	1.73 E-3	1.87 E-3	3626.1	150	543915
Particulates	1934619	2.77 E-4	2.77 E-4	3.00 E-4	580.6	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	305815	2.53 E-3			773.7	3	2321
CO2	305815	1.87 E+0			571874.1	1	571874
NOx	305815	1.59 E-3			486.2	150	72937
HC	305815	7.56 E-4			231.2	28	6473

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	305815	0.33			748.8	63	47176

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	602	12	23		72.2	4500	325080	1.00	72.24
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	7725	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 3328330 kg

Annual Equivalent Mass of CFC-11 : 72.24 kg

Table B-11 Environmental Impact : 100% Fossil-Fuel Generation
Large Office Building : System 3a

Electrical Generation / Transmission

Emitted Component	Energy Consumed kWh	Fossil Generation Emission Factor kg/kWh	System Emission Factor kg/kWh	Purchased Energy Factor kg/kWh	Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CO2	2219329	8.39 E-1	8.39 E-1	9.09 E-1	2017353.2	1	2017353
SO2	2219329	8.88 E-3	8.88 E-3	9.62 E-3	21351.7	0	0
NOx	2219329	1.73 E-3	1.73 E-3	1.87 E-3	4159.7	150	623961
Particulates	2219329	2.77 E-4	2.77 E-4	3.00 E-4	666.0	0	0

Natural Gas Combustion

Emitted Component	Energy Consumed m3	Combustion Emission Factor kg/m3			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
Engine :							
CO	0	1.92 E-2			0.0	3	0
CO2	0	1.86 E+0			0.0	1	0
NOx	0	1.76 E-2			0.0	150	0
HC	0	1.90 E-3			0.0	28	0
Soot	0	3.80 E-5			0.0	0	0
Burner :							
CO	127464	2.53 E-3			322.5	3	967
CO2	127464	1.87 E+0			238357.7	1	238358
NOx	127464	1.59 E-3			202.7	150	30400
HC	127464	7.56 E-4			96.4	28	2698

Natural Gas Transmission

Emitted Component	Energy Consumed m3	Leakage Factor %			Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg
CH4	127464	0.33			312.1	63	19663

Refrigerant Loss

Emitted Component	System Charge kg	Loss Factor % / year	System Lifetime years		Quantity of Emission kg	Global Warming Potential ; 20 years	Equivalent Mass of CO2 kg	Ozone Depletion Potential	Equivalent Mass of CFC-11 kg
CFC-11	602	12	23		72.2	4500	325080	1.00	72.24
HCFC-22	-	-	-		-	4100	-	0.05	-
LiBr/H2O	7725	0	23		0.0	0	0	0.00	0

Annual Equivalent Mass of CO2 : 3258480 kg

Annual Equivalent Mass of CFC-11 : 72.24 kg

APPENDIX E

COMMERCIALLY AVAILABLE GAS FIRED COOLING EQUIPMENT

COMMERCIALLY AVAILABLE GAS FIRED COOLING EQUIPMENT

As part of the Phase I, State-of-the-Art-Assessment, contact was established with 18 manufacturers or manufacturers representatives to obtain technical specifications on gas-fired cooling equipment. Tables 1, 2 and 3 summarize performance and feature information on the products offered by the various companies.

The performance data will be useful during the gas-fired cooling potential assessment. Representative equipment performance data will be used in computer simulations to determine energy use, electrical demand performance and operating costs of the various gas-fired technologies selected.

The information in Tables 1,2 and 3 is currently incomplete but will be updated as information is received from the remaining manufacturers. A list of the manufacturers or representatives contacted is also enclosed.

Table 1 Commercially Available Absorption Air-Conditioning Equipment Specifications

Company	Equipment Type	Cooling Capacity Range	Claimed Cooling Efficiency*	Claimed Heating Efficiency*	Absorption Cycle Type	Absorption Fluid Type	Features
Trane Co. 4051 Gordon Baker Rd. Scarborough, Ont. M1W 2P3	Commercial Direct-Fired Absorption Chiller	100 to 1100 tons (315 to 3866 kW)	COP up to 1.0	-	Double-effect reverse cycle	-	Available as a chiller/heater (space cooling & DHW). High efficiency heat economizer (exhaust gas recovery).
Gas Energy, Inc. (Hitachi) 166 Montague St. Brooklyn, NY U.S.A. 11201-9871	Commercial/Industrial Direct-fired water chiller/heater PARAFLOW	120 to 200 tons (420 to 703 kW)	COP = 1.12	COP = 0.9	Double-effect	LiBr / Water	Cogeneration Heat Recovery Water Chiller/ Heater available.
		250 to 1500 tons (880 to 5270 kW)	COP = 1.02	COP = 0.9	Double-effect	LiBr / Water	
American Yazaki Corp. 13740 Omega Rd. Farmers Branch, TX U.S.A. 75244-4516	Commercial Direct-fired water chiller/heater AROACE	20 to 50 tons (70 to 176 kW)	COP = 0.95	COP = 0.83	Double-effect	LiBr / Water	Waste-Heat-Fired Heat Recovery Single-Effect Chiller available.
		60 to 100 tons (210 to 351 kW)	COP = 1.00	COP = 0.83	Double-effect	LiBr / Water	
The Dometic Corp. 509 S. Poplar St. LaGrange, IN U.S.A. 46761	Air-Cooled Water-Chiller A/C Res. Split-System	3,4,5 tons (10.5,14,15.6 kW)	COP = 0.48	-	Single-effect	Ammonia / Water	
	A/C Res./Com. Packaged	8,10 tons (28, 35 kW)	COP = 0.48	-	Single-effect	Ammonia / Water	
	A/C Com. Split-System (multiple 5 ton units)	10 to 25 tons (35 to 88 kW)	COP = 0.48	-	Single-effect	Ammonia / Water	
	Air-Cooled Water-Chiller/Heater All-year A/C Res. Packaged or Split System	3,4,5 tons (10.5,14,15.6 kW)	COP = 0.48	-	Single-effect	Ammonia / Water	
Osaka Gas Co. Toho Gas Co. TokyoGas Co. Kawasaki Ind. Ltd.	Commercial Chiller/Heater GASMAX	100, 150, 200 tons (351, 527 703 kW)	COP = 1.26	?	?	?	

* excludes electrical power input

Table 2 Commercially Available Engine-Driven Air-Conditioning Equipment Specifications

Company	Equipment Type	Cooling Capacity Range	Claimed Cooling Efficiency	Claimed Heating Efficiency	Engine Type (Compressor Type)	Features
Trane Co. 4051 Gordon Baker Rd. Scarborough, Ont. M1W 2P3	Commercial Water-Cooled Chiller (EDC) (Using HCFC-22)	55, 80 tons (190, 280 kW)	-	-	Cylinder HERCULES engine	Heat recovery from engine water jacket & exhaust gas for DHW use or Desiccant regeneration
Yamaha Motor Ltd. 480 Gordon Baker Rd. North York, Ont. M2H 3B4	Residential Heat Pump A/C	1.3 to 5.3 tons (4.6 to 18.6 kW)	-	-	1,3,4 Cylinder OHV engine w/ rotary or scroll Yamaha compressor	
Thermo King Corp. 314 West 90th St. Minneapolis, MN U.S.A. 55420	Small Commercial packaged, rooftop mounted, air-cooled, single zone, heating/cooling A/C unit	15 tons (52.7 kW)	COP up to 0.91 (IPLV = 0.77)	-	4 Cylinder White HERCULES engine 163 cu/in. each; 40 BHP @ 2400 rpm. 4 Cylinder reciprocating compressors Thermo King X430 open-drive type.	Cooling only. Fresh air vent. (economizer). Reheat (dehumidification). Engine heat recovery.
Tecogen, Inc. 45 First Avenue P.O. Box 9046 Waltham, MA U.S.A. 02254-9046	Commercial Water-Cooled Chiller TECOCHILL w/ R11	230, 460 tons (808,1616 kW)	COP = 1.7 (IPLV = 2.0)	-	1 or 2 TecoDrive engine modified 454 cu/in. G.M V8 directly-coupled to open-drive centrifugal compressors	Heat recovery package that yields as much as 1,700,000 Btu/h of hot water. Load following with variable-speed drive engine.
	Commercial Water-Cooled Chiller TECOCHILL w/ R22	100, 125 tons (351, 439 kW) 150, 175 tons (527, 615 kW)	COP* = 1.8 COP** = 1.3 COP* = 1.9 COP** = 1.4	-	One TecoDrive engine modified 454 cu/in. G.M V8 directly-coupled to open-drive screw compressors (Howden Twin Screw)	Heat recovery package that yields as much as 810,000 Btu/h of hot water. Load following with variable-speed drive engine.
Gemini Energy Systems, Inc. P.O. Box 9258 Corpus Christi, TX U.S.A. 78469	Commercial Water-Cooled Chiller w/ R22 or Ammonia	30 to 200 tons (105 to 703 kW)	-	-	2 to 6 Cylinder, Gemini engine w/ 4 to 8 cylinder, Gemini reciprocating compressors.	Heat recovery from engine water jacket & exhaust gas Load following with variable-speed drive engine.

* w/ Heat Recovery

** w/o Heat Recovery

Table 3 Commercially Available Desiccant-based Air-Conditioning Equipment Specifications

Company	Equipment Type	Cooling Capacity Range	Claimed Cooling Efficiency	Claimed Reactivation Energy	Cycle Type	Desiccant Type	Features
Munters Cargocaire 79 Monroe St. P.O. Box 640 Amesbury, MA U.S.A. 01913	Supermarket and Small/Medium Commercial Packaged , Rooftop mounted Desiccant-based A/C SUPERADD SUPERAIRE	20 to 80 tons (70 to 280 kW) 120 to 240 lbs/hr (54.5 to 109 kg/hr) water removal rate	-	375 to 600 Mbtu/hr (110 to 175 kW) input maximum	Integrated Open-Cycle	Solid (Silica or Lithium Chloride)	Precooling coil (optional). Units can be added to existing HVAC system.
ICC Technologies 441 North Fifth St. Philadelphia, PA U.S.A. 19123	Supermarket and Small/Medium Commercial Packaged , Rooftop mounted Desiccant-based make-up air and desiccant dehumidification w/ cogeneration A/C units DESI/AIR DESI/GEN	- up to 500 lbs/hr (up to 227 kg/hr) water removal rate	-	up to 600 Mbtu/hr (up to 175 kW) input maximum	Integrated Open-Cycle	Solid (Silica gel)	DESI/GEN units include cogeneration system providing up to 150 kW of electricity and thermal energy for both space and water heating. Variable speed drives (optional)

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