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Project Summary

Alternative Technologies for Refrigeration and Air-Conditioning Applications

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A study was conducted to assess refrigeration technologies which are alternatives to vapor compression refrigeration for use in five application categories: domestic air conditioning, commercial air conditioning, mobile air conditioning, domestic refrigeration, and commercial refrigeration. A fundamental criterion for the selection of the alternative refrigeration technologies to be assessed was that they be environmentally safe.

The study was conducted in three phases: a survey of U.S. patents, system modeling, and a technology assessment. Each refrigeration application was defined by a set of thermal source and sink temperatures. The U.S. patent survey was conducted from 1918 to the present. A method was developed for classifying refrigeration technologies found during the survey.

Thermodynamic models were developed for the alternative refrigeration cycles. A computer program was written using these thermodynamic models to conduct a parametric study of the cycle efficiency of the alternative refrigeration technologies.

A method for assessing and comparing the refrigeration technologies was developed. Six technical assessment criteria were identified: state-of-the-art, complexity, size and weight, maintenance, useful life, and efficiency.

It was concluded that the most promising alternative refrigeration technologies to vapor compression were absorption and solid sorption. From environmental and economic standpoints, none of the alternative refrigeration technologies were as attractive as adapting vapor compression refrigeration to non-chlorofluorocarbon refrigerants.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The vapor compression cycle is presently the most widely used method of cooling for domestic, commercial, and mobile air conditioning and refrigeration. Vapor compression technology has been developed to its present level of maturity by using chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. These refrigerants have excellent thermodynamic properties for cooling cycles. They are inexpensive, stable, nontoxic, and (until 1974) were thought to be environmentally safe. In 1974, a paper was published hypothesizing the potential destruction of upper atmosphere ozone due to the release of chlorofluoromethanes. This naturally occurring ozone in the upper atmosphere shields the Earth's surface from ultraviolet (UV) radiation emitted from the sun. Depletion of ozone results in the additional transmittance of UV band electromagnetic radiation to the Earth. Overexposure to UV radiation has been linked to skin cancer and other medical problems in humans and other animals.

Refrigeration equipment utilizing the vapor compression cycle is capable of cooling performance which has been considered acceptable in areas where a ready supply of low-cost electricity is available. Vapor compression machinery also has the advantages of low first cost and high reliability, compared to other existing refrigeration methods. This is due to its high level of development.

Recently, two global problems have caused the engineering community to explore alternatives to vapor compression refrigeration:

- Global environmental changes brought about by ozone depletion in the upper atmosphere and global warming.
- The continuing need and an increased desire for refrigeration in parts of the world where electricity is not readily available or economical.

Global warming is caused by the release of greenhouse gases into the atmosphere. Of all carbon dioxide (CO_2) emissions, 75% are from fossil fuel combustion. The release of HCFC and CFC refrigerants also contributes to the greenhouse effect. Some of these gases have a longer atmospheric lifetime and a much higher global warming potential (GWP) than CO_2.

Refrigeration systems can make two potential contributions to the greenhouse effect: (1) The direct GWP contribution results from the release of refrigerants with a high GWP into the atmosphere, and (2) The indirect GWP results from the creation of CO_2 during the combustion of fossil fuels to produce work to drive mechanical systems or to convert the fossil fuel energy to thermal energy to drive heat-driven systems.

Project Objective

The objective of this project was to identify, analyze, and assess refrigeration technologies which could serve as alternatives to vapor compression refrigeration.

Project Description

This project was conducted in three phases: (1) Identification and classification of refrigeration technologies, (2) Thermodynamic analysis of some of the more promising cycles, and (3) Technical assessment of the alternative technologies.

The U.S. patents and the technical literature were used as sources for identifying the different means of refrigeration. Once a representative group of refrigeration method concepts had been identified, a method of classifying them for thermodynamic analysis was developed.

The reversed Brayton, reversed Stirling, magnetic, thermoacoustic, thermoelectric, and pulse-tube refrigeration thermodynamic cycles were analyzed in detail. A computer model was developed for each of these cycles, and computer subroutines were written for each model. An interactive program was written to allow users to choose cycles they wished to consider and to vary specific parameters on a case-by-case basis. The program was used to provide an estimate of both the coefficient of performance (COP) and the thermodynamic (Second Law) efficiency for the cycles.

The final phase of this project was a technical assessment of refrigeration concepts. Criteria which were common to all refrigeration systems were identified. These criteria were rated on a scale of 1 (very low) to 5 (very high) for each technology and application category. A computer program was written to rank the refrigeration technologies from best to worst for each application area.

Discussion

Identification of Refrigeration Technologies

Phase 1 of this study involved identifying refrigeration technologies for the purposes of further analysis and technical assessment. U.S. patents and literature were surveyed to identify refrigeration methods known to the technical community from 1918 to the present. The literature survey was conducted in parallel with the patent survey.

The initial search for refrigeration patents was conducted manually for patents granted between 1918 and 1950. A list was compiled of U.S. patent classes and subclasses related to refrigeration and air conditioning. The patent classes and subclasses were used to locate patent numbers in the *U.S. Patent Index* for each calendar year being surveyed. The patent number was used to locate the abstract for the patent abstract in the *Official Gazette of the United States Patent Office*.

Databases are available which contain a complete listing of all U.S. patent titles and abstracts granted from 1950 to the present. The patents relating to a particular technology can be located in the database by supplying the computer with a list of the appropriate class and subclass numbers. Class and subclass numbers which had been identified during the manual patent search were used to locate refrigeration patent abstracts within the database. The abstracts were reviewed to determine the nature of the patents. Patents were accepted or rejected based on abstract information.

Approximately 2140 patent titles and abstracts were surveyed. Approximately 800 of these were from 1918 to 1950, and the remainder were for the post-1950 period. Since many of the refrigeration concepts found during the patent survey were similar, patents that were representative of those found in the survey were selected to avoid redundancy.

Once a representative sample of refrigeration technologies was found, they were classified into categories which had similar thermodynamic cycles.

Classification of Refrigeration Technologies and Applications

Two classification systems were developed for this study: the first to classify refrigeration technologies which had been identified during the U.S. patent and literature survey, and the second to define the types of applications in which the refrigeration technologies would be used with a set of thermodynamic source and sink temperatures.

During the review of the U.S. patents found during the patent survey, it was determined that the technologies fell into groups that could be defined by the thermodynamic cycle used for refrigeration. These cycles were used to categorize the refrigeration technologies for the thermodynamic analysis and technical assessment phases of the project (Phases 2 and 3).

The refrigeration technology categories considered during this project were absorption, adsorption, pulse-tube and thermoacoustic, magnetic, reversed Brayton, reversed Stirling, thermoelectric, and vapor compression.

The temperatures of the thermodynamic source (from which heat is accepted) and sink (to which heat is rejected) were established for each application. A search of refrigeration industry standards and other technical literature was conducted to determine a practical set of source and sink temperatures for each application area. Based upon this survey, a set of source and sink temperatures was established for each of the five application categories. Table 1 summarizes the five refrigeration categories and the source and sink temperatures used for comparing refrigeration technologies in each category. Four source temperatures were used for commercial refrigeration. These source temperatures are for Refrigeration Groups I through IV in the Air-Conditioning and Refrigeration Institute (ARI) Standard 420-1977, *Standard for Unit Coolers for Refrigeration*.

Table 1. Thermal Source and Sink Temperatures for Five Refrigeration Categories

Refrigeration Category	*Source Temperature (°C)*	*Sink Temperature (°C)*
Domestic Air Conditioning	*25.0*	*35.0*
Commercial Air Conditioning	*25.0*	*35.0*
Mobile Air Conditioning	*25.0*	*35.0*
Domestic Refrigeration	*-18.0*	*35.0*
Commercial Refrigeration:		
ARI Group I	*2.8*	*35.0*
ARI Group II	*1.7*	*35.0*
ARI Group III	*-2.2*	*35.0*
ARI Group IV	*-23.3*	*35.0*

Refrigeration Technology Modeling

An interactive computer program was written in FORTRAN to analyze the regenerative and non-regenerative reversed Brayton, reversed Stirling, thermoelectric, pulse-tube, thermoacoustic, and magnetic refrigeration cycles. The program calculates the COP and cycle efficiency for source temperatures from -24 to 28°C and a fixed sink temperature of 35°C (or changed to another value by the user).

Thermodynamic property routines were developed for air, helium, and gadolinium (a magnetic solid used as the working material in magnetic refrigerators).

Technical Assessment of Refrigeration Technologies

The assessment of refrigeration technologies involved the evaluation of two fundamental criteria common to all refrigeration and air-conditioning applications: environmental acceptability and system cost.

Environmental Acceptability

Environmental acceptability considerations include:

1 Ozone depletion potential (ODP) of the working material

2 Global warming potential of the refrigeration technology.

3 Toxicity of the working material.

4 Flammability of the working material.

5 Noise generated by the refrigeration system hardware.

Only refrigeration technologies capable of using working materials which are *not* ozone depleting were considered in this study.

Cost-Related Technology Assessment

Cost-related technology assessment considerations include:

1 State-of-the-art. Some alternative refrigeration technologies are more mature than others. Research and development were considered in two broad areas: basic technology development and system development. For this study, a basic technology was defined as one which is not unique to refrigeration and would have many potential applications in other areas. Generally, improving a basic technology is extremely expensive and there are no guarantees of success. System development refers to refining a refrigeration technology until it is market-ready.

2 Size and weight. Size and weight considerations are important for many refrigeration applications. Larger, heavier systems with the same cooling capacity as smaller, lighter systems contain more raw material, which increases the capital costs of the system. Increased size and weight create higher capital costs for structures in which they are used or reduce the usable space within the structures, this is particularly true in transportation applications.

3 System complexity. Assessment of system complexity includes considerations regarding the number and simplicity of subsystems, number of moving parts, and uncommon materials used in a refrigeration system. The difficulty in manufacturing the system, including likely manufacturing techniques and precision, and the cost of the working material and controls were also considered. These issues relate directly to the capital cost of the refrigeration system.

4 Useful life. Useful life of the refrigeration system is defined as the length of time during which the major components remain functional while operating with a nominal duty cycle and receiving normal maintenance. For example, the useful life of a domestic central air conditioner would be the life of the compressor, the major system component expected to have the shortest useful life.

5 Maintenance. Maintenance cost considerations include the amount of repair and preventive maintenance required, skill level of maintenance personnel, portion of time an operator would need to attend to the system, likelihood of component failure, and recurring costs (such as recharging a refrigeration system with working material as needed over the life of the system) for normal system operation.

6 Efficiency. Two factors are affected by the efficiency of the system: the cost to operate the refrigeration system and the indirect GWP. It was assumed for this study that all heat or electricity required to operate the refrigeration systems originated from the combustion of fossil fuels. The efficiency criterion rating is based on the cycle efficiency (fraction of the Carnot COP) at which the refrigeration system would operate for a particular application. This rating is based on what is technically feasible in the 1990s. As technology advances, the cycle efficiency of some less mature technologies may improve. Therefore, some of these technologies may become more attractive in the future.

Rating Factors

Numerical rating factors were assigned to assess the individual technical assessment criteria for each refrigeration technology. Each rating factor is the investigator's best estimate, on a scale of 1 (very low) to 5 (very high), of the merit of a particular technology for a technical assessment criterion. A rating of 5 for a criterion would indicate that it is particularly attractive for a technology. A rating of 1 would indicate that it is very unattractive with respect to the criterion being considered. Table 2 summarizes the linguistic interpretation of the extreme ratings (1 and 5) for each criterion. The rating numbers for the efficiency criteria are listed in Table 3.

Table 2. Literal Definition of the Numerical Ratings for Technology Assessment Criteria

Tech. Assessment Criterion	*Rating of 1*	*Rating of 5*
State-of-the-Art	*Theory Only*	*Fully Matured*
Complexity	*Very Complex*	*Very Simple*
Size and Weight	*High*	*Low*
Maintenance	*High*	*Low*
Use Life	*Short*	*Long*
Efficiency	*0.0 to 0.12*	*Above 0.50*

Table 3. Numerical Definition of the Efficiency Criteria Rating Scale

Efficiency Rating No.	*Cycle Efficiency Range*
1	*0.000 ≤ 0.125*
2	*> 0.125 ≤ 0.250*
3	*> 0.250 ≤ 0.375*
4	*> 0.357 ≤ 0.500*
5	*> 0.50*

Technical Assessment Ratings for the Refrigeration Technologies

To rate suitability of refrigeration technologies for domestic, commercial, and mobile air conditioning and domestic and commercial refrigeration, an algebraic expression was developed:

$$\Omega = \sum_{i=A}^{F} wf_i \times i \qquad (1)$$

where

Ω = the overall technology rating, di mensionless

wf_i = the technical assessment weighting factor for each criterion, fraction

A, B,...,F = the individual technical assessment criterion rating for each technology.

The individual weighting factors, wf_i, are chosen so that their sum equals 1; i.e.,

$$\sum_{i=A}^{F} wf_i = 1.0 \qquad (2)$$

Weighting factors were developed for each application to rank the relative importance of each of the six criteria for each type of application.

A computer program using Equation (1) was developed to calculate the overall technology rating, Ω, and rank the refrigeration technologies from high to low based on the value of Ω for each technology.

Results of Technology Assessment and Summary of Conclusions

The alternative refrigeration technologies considered during this project were rated using the computer program applying Equation (1), the numerical technology assessment rating data presented for each technology, and the weighting factors. The data in the computer program are a numerical summary of the patent search, numerical modeling, and technology assessment information developed during this project.

Technology Assessment Criteria Weighting Factors

Technology assessment criteria weighting factors were developed for each of the five applications areas. The value of each of these weighting factors was chosen to reflect the relative importance of the six criteria (state-of-the-art, complexity, size and weight, maintenance, useful life, and efficiency) for each application (Table 4).

Results

Domestic Refrigeration

Table 5 contains the technology ratings for domestic refrigeration. The technology ratings are distributed into four groups:

1 **High (Rating of 4.60)** Vapor compression was the most suitable technology for domestic air conditioning.

2 **Medium (Rating of 3.70 to 3.25)** Absorption received a medium rating. Absorption systems are characterized by a high cycle efficiency; however, the absorption refrigeration technology was penalized for use in domestic refrigeration because of additional complexity increased size, increased maintenance, and shorter useful life than vapor compression systems. The hardware for the reversed Stirling refrigeration cycle is compact. However, additional heat transfer loops are required so that the heat exchangers used in the reversed Stirling system can be in communication with the thermal source and sink. These additional heat transfer loops add to the complexity (and capital cost) of the refrigerator and reduce the cycle efficiency which is already low when compared to the cycle efficiency of domestic refrigeration systems using vapor compression.

3 **Low (Rating of 3.05 to 2.60)** The solid sorption, reversed Brayton, and pulse-tube/thermoacoustic technologies received low ratings. Presently, solid sorption refrigeration and the pulse tube/thermoacoustic technologies are immature. Therefore, the cost to develop these refrigeration technologies into marketable domestic refrigeration systems probably will be high.

4 **Very Low (Rating of 2.20 to 1.95)** Two technologies (thermoelectric refrigeration and magnetic refrigeration) received the lowest rating for domestic refrigeration. Both technologies have very low cycle efficiencies. Another limiting feature of thermoelectric refrigeration is the small amount of tellurium-based material which is available for producing the semiconductors used in thermoelectric cooling modules. Furthermore, the maximum temperature lift for a single stage of thermoelectric refrigeration is approximately 22°C which is insufficient for refrigeration, making it necessary to cascade thermoelectric systems in order to achieve the required source temperatures. This would further reduce the already low cycle efficiency.

Magnetic refrigeration technology is immature. The principal technical area which must be developed to achieve higher cycle efficiencies is regenerative heat transfer with a very high effectiveness.

Domestic Air Conditioning

Table 6 contains the refrigeration technology ratings for domestic air conditioning. Four rating groups were observed for domestic air conditioning.

1 **High (Rating of 4.80)** Vapor compression received the highest rating for use in domestic air conditioning.

2 **Medium (Rating of 3.80)** Absorption received a medium rating. Absorption systems used in air conditioning are

Table 4. *Technology Assessment Criteria Weighting Factors by Refrigeration Application*

Assessment Criterion	Domestic AC	Commercial AC	Mobile AC	Domestic Refrif.	Commercial Refrig.
State-of-the-Art	0.20	0.20	0.15	0.20	0.20
Complexity	0.15	0.10	0.20	0.20	0.10
Size and Weight	0.05	0.05	0.30	0.10	0.05
Maintenance	0.15	0.15	0.20	0.10	0.15
Useful Life	0.15	0.20	0.05	0.15	0.20
Efficiency	0.30	0.30	0.10	0.25	0.30

Table 5. *Ranking of Domesitc Refrigeration Technologies from Most to Least Favored*

Ranking	Refrigeration Technology	Rating
1	Vapor Compression	4.60
2	Absorption	3.70
3	Reversed Stirling	3.25
4	Solid Sorption	3.05
5	Reversed Brayton	2.65
6	Pulse-Tube/Thermoacoustic	2.60
7	Thermoelectric	2.20
8	Magnetic Refrigeration	1.95

Table 6. *Ranking of Domestic Air-Conditioning Technologies from Most to Least Favored*

Ranking	Refrigeration Technology	Rating
1	Vapor Compression	4.80
2	Absorption	3.80
3	Pulse-Tube/Thermoacoustic	2.95
4	Reversed Stirling	2.90
5	Solid Sorption	2.80
6	Reversed Brayton	2.35
7	Thermoelectric	2.05
8	Magnetic Refrigeration	1.95

characterized by high cycle efficiencies and long useful lifetimes in air conditioning. However, the absorption refrigeration technology rating was penalized for domestic air conditioning because of additional complexity, increased size, and increased maintenance.

3 **Low (Rating of 2.95 to 2.80)** The pulse-tube/thermoacoustic, reversed Stirling, and solid sorption technologies received a low rating for domestic air conditioning. The pulse-tube/thermoacoustic technology is immature, and has low cycle efficiencies at source temperatures of 20°C and above. The most promising technology in this group for domestic air conditioning is solid sorption. The cycle efficiency of solid sorption systems should be high in the temperature lift range used for air conditioning.

4 **Very Low (Rating of 2.35 to 1.95)** The reversed Brayton, thermoelectric refrigeration, and magnetic refrigeration were rated as having very low suitability for domestic air conditioning. The principal reasons for the very low rating of the reversed Brayton technology are: a large physical size per ton of cooling effect of the hardware (compressor, expander, and ducts), high complexity (and therefore high capital cost) of the turbine and expander, and a low cycle efficiency.

Mobile Air Conditioning

Table 7 contains the refrigeration technology ratings for mobile air conditioning. The technologies are ranked from the most to least favored. The size and weight criteria were given a high relative importance and the efficiency criterion weighting was reduced for mobile air conditioning (Table 3). The useful life of mobile air conditioning systems is also shorter than for the other four application areas (a 10-year average life was used as an estimated life of mobile air conditioners for this study). The refrigeration technology ratings in Table 7 were considered to be in four groups of suitability for mobile air conditioning:

1 **High (Rating of 4.30)** Vapor compression was rated highest. The primary reasons for rating were a relatively low weight and small hardware size per ton of cooling effect in mobile cooling. Mobile vapor compression cooling systems also require little maintenance and are relatively inexpensive to produce.

2 **Medium (Rating of 3.25)** The reversed Stirling technology was rated as medium for mobile cooling. The important attributes of reversed Stirling technology for mobile cooling are compactness and low maintenance of the refrigeration system. The low cycle efficiency, particularly at higher source temperatures, was the principal reason that reversed Stirling did not receive a high rating for mobile cooling.

3 **Low (Rating of 2.65 to 2.30)** The pulse-tube/thermoacoustic, solid sorption, reversed Brayton, and absorption technologies received low ratings for mobile air conditioning. The primary reasons for the low rating was the large size and high weight per ton of cooling capacity as compared to vapor compression systems.

4 **Very Low (Rating below 2.15)** Thermoelectric cooling and magnetic refrigeration were rated lowest for mobile air conditioning. The reasons for the very low rating were a low cycle efficiency and the need for a large electrical generation system aboard the vehicle for both technologies.

Commercial Air Conditioning

Table 8 contains the refrigeration technology ratings for commercial air conditioning. The suitability ratings are distributed into three groups:

1 **High (Rating of 4.85 to 4.45)** Vapor compression was the most suitable technology for commercial air conditioning. Absorption was also rated high. Since commercial air-conditioning systems generally have a larger cooling capacity and longer life expectancy than domestic systems, they were not penalized as heavily for ad-

Table 7. *Ranking of Mobile Air-Conditioning Technologies from Most to Least Favored*

Rankng	*Refrigeration Technology*	*Rating*
1	*Vapor Compression*	*4.30*
2	*Reversed Stirling*	*3.25*
3	*Pulse-Tube/Thermoacoustic*	*2.65*
4	*Solid Sorption*	*2.55*
5	*Reversed Brayton*	*2.50*
6	*Absorption*	*2.30*
7	*Thermoelectric*	*2.15*
8	*Magnetic Refrigeration*	*1.25*

Table 8. *Ranking of Commercial Air-Conditioning Technologies from Most to Least Favored*

Ranking	*Refrigeration Technology*	*Rating*
1	*Vapor Compression*	*4.85*
2	*Absorption*	*4.45*
3	*Pulse-Tube/Thermoacoustic*	*3.10*
4	*Solid Sorption*	*2.80*
5	*Reversed Stirling*	*2.75*
6	*Reversed Brayton*	*2.35*
7	*Magnetic Refrigeration*	*2.05*
8	*Thermoelectric*	*1.95*

ditional complexity and increased maintenance. Emphasis was placed on the efficiency of commercial air conditioning systems.

2. **Medium (Rating of 3.10 to 2.75)** The pulse-tube/thermoacoustic, solid sorption, reversed Stirling, and reversed Brayton technologies were in the medium suitability rating group. These gas cycle refrigeration technologies have low cycle efficiencies at the higher source temperatures used in air conditioning. Solid sorption refrigeration technology has the highest cycle efficiency in the medium group.
3. **Low (Rating of 2.35 to 1.95)** Thermoelectric and magnetic refrigeration have very low cycle efficiencies. Presently, the amount of tellurium-based material for semiconductors is limited. Therefore, the first cost of thermoelectric systems will be high. Magnetic refrigeration technology is immature. Highly effective regenerative heat transfer is the principal technical area which must be developed to improve the cycle efficiency of magnetic air conditioning.

Commercial Refrigeration

Table 9 contains the refrigeration technology ratings for commercial refrigeration. The suitability ratings are distributed into four groups:

1. **High (Rating of 4.70)** Vapor compression received the highest rating for commercial refrigeration.
2. **Medium (Rating of 3.80)** Absorption refrigeration was rated next highest. Although absorption refrigeration is capable of high cycle efficiencies, it is not as attractive as vapor compression from the perspective of complexity, size and weight, and maintenance (particularly for supermarkets).
3. **Low (Rating of 3.10 to 2.80)** The gas cycle refrigeration technologies (reversed Stirling, reversed Brayton, and pulse-tube/thermoacoustic refrigeration) were in the low suitability rating group. The cycle efficiencies of refrigeration systems using these technologies increase with decreasing source temperature. All of these technologies are best suited for cryogenic and low-temperature industrial refrigeration.
4. **Very Low (Rating of 2.05)** Thermoelectric and magnetic refrigeration were in the lowest suitability rating group for commercial refrigeration . Both of these technologies have very low cycle efficiencies.

Table 9. *Ranking of Commercial Refrigeration Technologies from Most to Least Favored*

Ranking	*Refrigeration Technology*	*Rating*
1	*Vapor Compression*	*4.70*
2	*Absorption*	*3.80*
3	*Reversed Stirling*	*3.15*
4	*Solid Sorption*	*3.10*
5	*Reversed Brayton*	*3.00*
6	*Pulse-Tube/Thermoacoustic*	*2.80*
7	*Magnetic Refrigeration*	*2.05*
8	*Thermoelectric*	*2.05*

Conclusions

- Vapor compression refrigeration using non-CFC refrigerants is the most desirable technology of those considered for use in the five application areas considered in this study (domestic, commercial, and mobile air conditioning; and domestic and commercial refrigeration). This conclusion is supported by the first place ranking that vapor compression received in the technical assessment of each technology (Tables 5 through 9).
- Absorption refrigeration is attractive for commercial refrigeration and air conditioning. If the complexity and maintenance levels can be reduced, it could also be attractive for domestic applications.
- Solid sorption refrigeration technology is immature. This technology may have some advantages over absorption systems using liquid absorbents, particularly for domestic refrigeration and air conditioning. Canister sorption and heat transfer efficiencies must be improved above present levels. Complete systems must be developed to demonstrate a reasonable useful life and acceptable maintenance levels. Solid sorption is the most promising new refrigeration technology in terms of technical feasibility, particularly for air conditioning and refrigeration, where batch processes can be used.
- The highest cycle efficiencies for the gas cycle refrigeration technologies (reversed Stirling, reversed Brayton, and pulse-tube/thermoacoustic) occur

at source temperatures below the lowest temperature considered in this study (-24°C). These technologies are best suited to low temperature refrigeration.

- The thermoelectric and magnetic refrigeration technologies are impractical for normal refrigeration and air conditioning at this time.

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The complete report, entitled "Alternative Technologies for Refrigeration and Air-Conditioning Applications," (Order No. PB95-224531; Cost: $44.50, subject to change) will be available only from:
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