Potential impacts of CFC restrictions on refrigeration and space-conditioning equipment*

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Several organizations have recently surveyed alternatives to the use of CFC compounds in refrigeration and space-conditioning applications. ORNL has conducted a preliminary analysis of potential energy-use impacts and an industry survey of R & D needs in response to CFC restrictions. Of the restricted compounds, R11 and R12 will have the major impact due to their wide use in automotive air conditioning, domestic and commercial refrigeration, and centrifugal chillers. Alternative refrigerants available in the short term include R22, R500, R502, and certain blends, but these are not suitable substitutes for all applications. R134a and R123 are environmentally acceptable substitutes which appear promising for new equipment, but information on them is preliminary and they will not be commercially available for several years. Blends of previously unused compounds present additional possibilities. Provided that the new refrigerants prove to be fully acceptable substitutes, long-term adverse energy-use impacts on new equipment will be minor. Impacts will be severe if identified substitutes prove to be unacceptable or if R22 is also restricted in the future. However, significant penalties may be incurred by the use of substitute insulation materials in appliances and buildings. Substitute refrigerants for existing equipment may be a major problem. Generation of comprehensive and accurate information on the engineering properties and health effects of R134a and R123 is an urgent R & D need. Cooperative efforts are needed. The potential use of refrigerant mixtures needs to be explored as replacement substitutes and for efficiency and modulation benefits that can be derived by the use of non-azeotropic mixtures. Alternative cycles need to be re-examined as back-up substitutes.
(Keywords: CFC; space-conditioning; R & D)

Impacts potentiels des restrictions de CFC sur les matériels de refroidissement et de conditionnement d'air

Plusieurs organisations ont récemment étudié des solutions de rechange à l'utilisation des CFC dans les applications du froid et du conditionnement d'air. L'ORNL a effectué une analyse préliminaire de l'impact potentiel sur l'utilisation de l'énergie et une étude des besoins de l'industrie en recherche-développement pour faire face aux limitations dans l'utilisation des CFC. Parmi les composés dont l'utilisation est limitée, le R11 et le R12 ont l'impact le plus important en raison de leur large utilisation dans le conditionnement d'air des automobiles, du froid ménager et commercial et dans les refroidisseurs à compresseur centrifuge. Les frigorigènes de rechange disponibles à court terme comprennent le R22, le R500, le R502 et certains mélanges, mais ceux-ci ne sont pas appropriés pour toutes les applications. Le R134a et le R123, qui sont acceptables pour l'environnement, semblent prometteurs pour de nouveaux matériels; cependant, les renseignements les concernant en sont au stade préliminaire; ces frigorigènes ne seront pas commercialisés avant plusieurs années. Les mélanges de composés inutilisés jusqu'ici présentent des possibilitiés supplémentaires. A condition que les nouveaux frigorigènes se révèlent être entièrement acceptables, l'impact défavorable à long terme de l'utilisation de l'énergie sur les nouveaux matériels est peu important. L'impact sera sérieux si les produits de remplacement identifiés se révèlent inacceptables ou si l'utilisation de R22 est limitée aussi à l'avenir. Cependant, des inconvénients importants peuvent être encourus par l'utilisation d'isolants de remplacement dans les appareils et les bâtiments. Les frigorigènes de remplacement pour les matériels existants peuvent constituer un problème majeur. La production de renseignements complets et précis sur les propriétés techniques et les effets sur la santé du R134a et du R123 est un besoin urgent de recherche-développement. Des efforts de coopération sont nécessaires. Pour remplacer les halogènes, il est nécessaire d'examiner les conditions d'utilisation de mélanges de frigorigènes, et d'apprécier les avantages en ce qui concerne le rendement et la régulation des mélanges non azéotropiques. Les cycles de remplacement devront être réexaminés comme moyen complémentaire.
(Mots clés: CFC; conditionnement des locaux; recherche-developpement)

The USA and 23 other countries signed the Montreal Protocol[1] in September 1987 to protect the stratospheric ozone layer from harmful emissions of chlorinated and brominated compounds. The US Environmental Protection Agency (EPA) subsequently issued a Notice of Proposed Rulemaking[2] in December 1987 which will implement the provisions of the protocol when it is approved by the US Senate. The treaty calls for stringent production controls on a wide range of chlorofluorocarbons (CFCs); freezing production at 1986 levels for several years and then mandating a 20% reduction in 1993 and cutting to just 50% of 1986 levels in 1998. As a result, US and foreign manufacturers of refrigeration and

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space-conditioning equipment will soon be faced with modifying or redesigning their product lines to accommodate these cutbacks or with discontinuing the use of the conventional refrigerants that are affected by the proposed regulations.

The social, economic, and energy-use impacts in the USA appear substantial considering our dependence on these compounds in refrigeration equipment. It is the purpose of this Paper to examine the energy-use impacts that might occur as a result of restrictions on commonly used refrigerants and to define the necessary R & D that can help mitigate the extent and duration of these adverse impacts. While the focus of this analysis is on the USA, similar impacts can be expected in other countries and geographic areas.

The authors have conducted a preliminary analysis of the potential energy-use impact of CFC restrictions[3] and an industry survey of perceived R & D needs in response to restrictions and have formulated an R & D plan that they are recommending for cooperative implementation by industry and the Federal Government[4]. These activities provide the background for this Paper.

Applications impacted

The refrigerants identified for restriction are R11, R12, R113, R114 and R115. All except R113 are used to some extent in the applications of concern here; R113 is used mainly as a cleaning solvent by the electronics industry. R11, R12, and R114 are used in refrigeration equipment, commercial chillers, and automobile air conditioners. R115 is not normally used by itself as a refrigerant, but it is a constituent of the azeotropic refrigerant R502, which is used in commercial refrigeration equipment. Besides being widely used by itself, R12 is also a constituent of R500 which is used in chillers.

Table 1 shows the amounts of these refrigerants used annually in the USA in refrigeration and space-conditioning applications. Clearly R12 represents the major usage and the source of the major energy-use impact.

In addition to their use as working fluids in refrigeration equipment, R11 and R12 are also used as blowing agents in the manufacture of flexible and rigid foam materials. Extruded polystyrene, polyurethane, and polyisocyanurate are rigid foams that are used as building and appliance insulation. Any change in the availability or insulating properties of these materials resulting from restrictions on R11 and R12 will also have significant effects on applications such as refrigerators where both the insulation and working fluid are affected.

Table 1 US consumption of restricted CFCs by application
Tableau 1 *Consommation aux Etats-Unis des CFC réglementés, par application*

Application	Annual consumption (1000 metric tons)				
	R11	R12	R114	R500	R502
Automobile air conditioning	–	54.1	–	–	–
Domestic refrigerator/freezer	–	2.9	–	–	–
Retail food refrigerator/freezer	–	4.7	–	–	6.2
Food warehouse refrigeration	–	2.6	–	–	3.0
Space conditioning chillers	5.5	2.5	0.8	0.9	–
Rigid insulation manufacturing	38.5	8.7	–	–	–
Total	44.0	75.5	0.8	0.9	9.2

Energy-use impact

Gases considered

The first step in conducting the energy-use impact study was to select the specific applications for consideration that represent the major applications, nationwide, that will be affected by CFC restrictions. The next step was to identify the current practice in each case and then to consider four alternatives: near drop-in substitutes; conventional refrigerants; unconventional refrigerants; and alternative cycles.

The applications, current practice, and each of the four alternatives considered are listed in *Table 2*. The alternatives do not form a comprehensive, exhaustive list, but they serve to bracket the energy impacts of all the possibilities.

The near drop-in substitutes come close to matching the properties of R11 and R12 but have much lower ozone-depleting potentials (ODP) and are not on the list for production controls. The current most promising substitutes are R123 (1,1-dichloro-2,2,2-trifluoroethane) and R134a (1,1,1,2-tetrafluoroethane) for R11 and R12, respectively. Several of the selected applications use polyurethane foam insulation to minimize the

Table 2 Alternative refrigerants and insulating materials
Tableau 2 *Frigorigènes et isolants de rechange*

Application	Current practice	Near drop-in substitutes	Conventional refrigerants	Unconventional refrigerants	Novel cycles
Refrigerator/freezer	R12 with R11 foam insulation	R134a with R-123 foam	R22 with fibreglass insulation	Ammonia with fibreglass	Stirling cycle with vacuum panel insulation
Mobile air conditioning	R12	R134a	R22	Ammonia	Stirling cycle
Beverage vending machines	R12 with R11 foam insulation	R134a with R123 foam insulation	R22 with fibreglass insulation	Ammonia with fibreglass	Stirling cycle with vacuum panel insulation
Retail refrigeration	R502	R502	R22	Ammonia or propane	Stirling cycle
Centrifugal chillers	R11, R12, R114, R22 and R500	R134a, R123, and R22	R22 and current absorption	Ammonia and current absorption	Advanced absorption
Refrigerated transport	Diesel R12 with R11 foam insulation	Diesel R134a with R123 foam insulation	Diesel R22 with fibreglass insulation	Ammonia	Not considered

Table 3 Estimated national energy-use impacts of CFC alternatives
Tableau 3 *Impacts estimés de la consommation nationale d'énergie des substituts des CFC*

	National energy penalties ($EJ\ year^{-1}$)			
Application	Near drop-in substitutes	Conventional refrigerants	Unconventional refrigerants	Novel cycles
Refrigerator/freezer	0.12	0.59	0.94	−0.54
Mobile air conditioning	0.00	0.06	0.08	0.01
Beverage vending machines	0.01	0.03	0.06	−0.03
Retail refrigeration	0.01	0.01	0.02	−0.03
Centrifugal chillers	0.01	0.03	0.38	–[a]
Refrigerated transport	0.00	0.01	0.02	–[a]
Total	0.15	0.73	1.50	> −0.59

[a] Possible reduction

refrigeration load; it is assumed here that an alternative foam is used that is blown by R123 instead of R11.

The conventional refrigerants depend on using a common refrigerant (R22 here) in an application where normally it is not used as the working fluid; these are compounds that are not covered under the Montreal Protocol but are not entirely benign in their relation to stratospheric ozone either. There is still some concern that they may come under environmental scrutiny in the future.

The unconventional refrigerants considered, mainly ammonia and propane, have toxicity and/or flammability problems, which is why they are not commonly used in these applications; however, they do not present any threat to the ozone. Ammonia, of course, is used conventionally in some applications but is unconventional in the applications considered here. In the case of centrifugal chillers, absorption chillers are a conventional alternative, but they are put in the same category as unconventional refrigerants because they also represent a reserve alternative in case no conventional refrigerants can be used. In both cases, extensive component redesign and resizing would be required.

Finally, the alternative cycles are concepts with long-term potential that will require considerable development to reach commercial use. The Stirling cycle and advanced absorption cycles are the principal alternatives considered.

Methodology

The annual energy impacts were computed for each of the applications using a simplified analysis. Where possible, cycle calculations were performed at standard operating conditions or at test conditions using reasonable assumptions about compressor and motor efficiencies. This calculation required assuming that compressors can be developed or adapted to use the new refrigerants (i.e. R134a and R123) or for R22 under conditions where it is not used today. Differences in energy use between the alternatives and the current technology were combined with information on the present number of units in use nationwide to determine a national, annual energy-use impact. Projection is to some undetermined date in the future when there has been a complete replacement of equipment and R11, R12, R114, etc., are no longer in use at all in a particular application.

Results

The results listed in *Table 3* are given in terms of primary energy so that the electrically driven systems may be evaluated on the same basis as the fuel driven (i.e. mobile air conditioners, refrigerated transport, absorption chillers).

As expected, the penalties associated with use of the near drop-in substitutes are not particularly large. Domestic refrigerator/freezers comprise most of the impact; zero impact is shown for automotive air conditioning. For the case of conventional refrigerants, the impact is five times as large and of serious proportion. Here again, domestic refrigerator/freezers have the greatest impact with automotive air conditioning being second.

With conventional refrigerants impact is doubled, and centrifugal chillers now show a major contribution.

For the alternative cycles, an energy saving of almost 0.6 $EJ\ year^{-1}$ is estimated; however, most of this gain is from advanced evacuated-panel insulation in the refrigerator/freezer application.

R & D needs

New substitute refrigerants

R123 and R134a, as most other alkyl halides, have been known for some time but previously have not been considered seriously for use as refrigerants[5]. Information on their engineering properties and toxicity at present is preliminary. Neither compound is available in commercial quantities currently and minimum time to availability after commitment by chemical manufacturers is about 5 years. This period is needed for long-term toxicity tests and construction of manufacturing facilities and cannot be reduced. Available information on these compounds is not adequate to determine accurately whether their use will result in any loss in efficiency. An urgent need exists for better information on these compounds so that their use as substitutes can be examined rigorously. Information needed includes improved data on thermodynamic properties, transport property data, materials compatibility, and miscibility with lubricants.

No single-compound substitute for R114 has been identified, nor for R22 if it is eventually included under the protocol.

Chemical manufacturers claim that they have explored substitute compounds extensively and that it is unlikely that any reasonable candidates have been overlooked. This conclusion is probably true for alkyl halides; it is unlikely but not impossible that new, attractive substitutes of other classes of compounds might be identified. McLinden and Didion[6] have done a thorough review of single-component refrigerants and concluded that there is a limited number that are suitable as substitute working fluids. The possibilities in mixtures, though, are largely unexplored.

Substitute refrigerant mixtures

Refrigerant mixtures offer an approach to developing substitutes for restricted pure-compound refrigerants. An example is R22/R142b, a non-azeotropic mixture that has been proposed as a substitute for R12.

There are a number of compounds chemically similar to the common refrigerants that are not usable by themselves as refrigerants because of some undesirable characteristic such as flammability or inappropriate volatility but are candidates for use as a mixture constituent. To find a substitute for R12, for example, one would look at mixtures of a compound more volatile than R12 and one less volatile than R12 which together have about the desired volatility. The R22/R142b combination is such a mixture. The R142b is not usable by itself because it is flammable, but the mixture in the proposed proportions is non-flammable. In this case, R142b also happens to be available in commercial quantities.

Some examples of compounds not presently used as refrigerants that do not contain chlorine are R125 (CF_3CHF_2), R143a (CH_3CF_3), and R152a (CH_3CHF_2). Others have low chlorine content and would be expected to have low ODP; for example, R124 (CH_3CHFCl) and R142b (CH_3CClF_2).

Ternary and quaternary systems extend the range of possibilities considerably. We are not aware that any non-proprietary, comprehensive investigations of refrigerant mixture substitutes have been conducted.

Non-azeotropic refrigerant mixtures offer additional benefits which make them an interesting current research topic. Because they do not change phase at a discrete temperature, there is the possibility to increase cycle efficiency by matching the temperature profiles of the refrigerant to those of the source and sink fluids in the condenser and evaporator[7]. They also offer the possibility to modify capacity by shifting refrigerant composition[8]. Equipment must be designed specifically for use with non-azeotropic refrigerant mixtures to obtain the performance advantages.

Conventional and unconventional refrigerants

Technology for the use of R22 and ammonia is well established, and their unconventional use in the applications of concern here would require some product development activity but it is unlikely that R & D would be needed. It is probable that available information on the engineering properties of propane would be adequate, considering petroleum industry experience with this compound.

Alternative refrigeration cycles

Alternative refrigeration cycles such as absorption, Stirling, and desiccant systems are used conventionally in some applications but generally would be considered unconventional in applications considered here. Extensive R & D would be required in some cases before these cycles could be regarded as practical CFC alternatives.

Absorption was widely used for both domestic and commercial refrigeration in the early part of this century; it is still used in small refrigerators in recreational vehicles. It is also widely used as a chiller in commercial space conditioning although it is not as popular in the USA as an electric chiller. Expanded use of these technologies as CFC alternatives would not require R & D.

However, advanced absorption cycles are presently under development for commercial space-conditioning applications that are about 50% more efficient than conventional absorption chillers[9]. The development of these systems is at an early experimental stage, but prospects for technical success and economic competitiveness appear good. Current R & D issues are thermal design to achieve full efficiency potential, materials compatibility and corrosion resistance, and improved solution pump development. It is likely that commercialization of such systems will be successful independent of the CFC issue because of their exceptionally high heating efficiency. However, they also offer an alternative to CFC-based systems in both residential and commercial applications. This R & D should be pursued vigorously.

Stirling systems use working fluids that do not undergo a phase change. Hydrogen and helium are the preferred fluids although air is used for some applications. Cryogenic Stirling refrigerators are conventional in small laboratory and military applications. Stirling refrigerators have long been considered an academic possibility for domestic and commercial refrigeration, but 'conventional wisdom' is that Stirling is less efficient than vapour compression at low temperature lifts. Recent analytical studies tend to confirm this[10], but projected coefficients of performance (COPs) are still in a reasonable range. Moreover, Stirling is not subject to efficiency losses due to on–off cycling as is vapour compression. One development of a Stirling unit for use in a foreign domestic refrigerator was announced recently[11].

The computer codes used to investigate Stirling refrigerators lack experimental validation, and no reliable, relevant experimental data appear to be available. A comprehensive analytical and experimental programme to evaluate this alternative is needed.

Alternative cycles other than those used in the energy-use impact analysis are potential replacements for CFC-based vapour compression equipment. Desiccant and evaporative cooling systems are of particular interest.

Both liquid- and solid-bed-desiccant systems are used to control humidity in commercial space-conditioning systems. These are open-cycle, non-CFC systems that operate in direct contact with the conditioned air. Desiccant-based heating and cooling systems have been shown to be technically feasible and are potentially capable of operating at reasonable efficiency levels. Such systems are currently of interest as a means of converting waste heat from engine-driven heat pumps or cogeneration units into useful space heating and cooling[12]. Current R & D efforts do not appear adequate to fully evaluate the potential of this class of equipment.

Non-CFC evaporative cooling systems are conventional in arid regions of the USA. Equipment and energy costs are low, but maintenance requirements due to fouling are high and mechanical cooling is generally preferred. Presently, both direct and indirect evaporation systems are used in stand-alone and hybrid mechanical–evaporative units. This equipment is commercially available. R & D to reduce maintenance requirements could make this class of equipment more attractive[13].

Conclusions

The potential energy-use impacts of CFC regulations range from modest to severe, depending upon whether presently identified substitutes prove to be usable and whether additional CFC compounds are controlled in the future.

There are few alternatives available in the short term, say 0–5 years. Absorption chillers could be substituted for centrifugal chillers in commercial space-conditioning applications. It might be feasible to develop low-ODP refrigerant mixtures that are close substitutes for the controlled compounds. Switching to a conventional low-ODP refrigerant such as R22 is not a desirable alternative for most applications.

R123 and R134a appear promising as environmentally acceptable substitutes for R11 and R12, respectively, but these compounds will not be available in commercial quantities for at least 5 years. Existing information on their engineering properties is preliminary, and research to provide this information is needed urgently. If these alternatives are usable, the national energy-use penalty is estimated to be 0.14 EJ $year^{-1}$.

If R123 and/or R134a prove to be unacceptable and it becomes necessary to redesign equipment for use with a conventional, uncontrolled refrigerant (mainly R22), an energy-use penalty of 0.70 EJ $year^{-1}$ could result. If R22 were not available, it is estimated the penalty would be over 1.4 EJ/$year^{-1}$.

If R123 and R134a do not prove to be fully acceptable alternatives or if R22 use is restricted in the future, then refrigerant mixtures and/or alternative refrigeration cycles will have increased importance. Ultimately, alternative cycles could provide all the capability now provided by vapour compression systems, probably with a modest reduction in national energy use for the applications considered.

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