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# Planning Report

## Economic Assessment of the NIST Alternative Refrigerants Research Program

Prepared by:
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for
National Institute of
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Strategic Planning and
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# ECONOMIC ASSESSMENT OF THE NIST ALTERNATIVE REFRIGERANTS RESEARCH PROGRAM

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# EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) conducts research into the chemical and physical properties of alternative refrigerants used to replace chlorofluorocarbon (CFC)-based refrigerants. This case study assesses the economic benefits to U.S. industry of the research and investment that NIST has made in this area.

Refrigerants are chemicals used in machines (such as air-conditioning systems) that carry energy from one place to another. Until the past decade, most refrigerants used throughout the world were made up of CFCs due to their desirable physical and economic properties. However, some research has shown that the release of these CFC gases into the atmosphere can possibly damage the ozone layer of the Earth. In response to these findings, international legislation was drafted that resulted in the signing of the Montreal Protocol in 1987, a global agreement to phase out the production and consumption of CFCs and replace them with other compounds that would have less impact on the environment.

In order to meet the phase-out schedule in the Protocol, it was necessary to perform research into developing new types of refrigerants (called "alternative refrigerants") that would retain the desirable physical properties of CFCs, but would pose little or no threat to the ozone layer. Possible candidates for replacement must meet a number of important criteria in order to be judged feasible as replacements.

With the timetable imposed by the Protocol as an incentive to develop new alternatives to CFCs, NIST engaged in research that would allow industry to make the switch to alternative refrigerants in a timely and economic fashion. NIST began by identifying the basic requirements for new refrigerants according to the new rules, and then started research on determining the physical properties of such candidate alternatives.

The results of these research efforts were made available to industry. NIST most effective form of information dissemination has been the REFPROP program, a computer package that is available through NIST's Standard Reference Data Program. The REFPROP program is used by both manufacturers and users of alternative refrigerants in their respective manufacturing processes. A particular benefit of the REFPROP program is the ability to model the behavior of refrigerant mixtures, which has proven to be a key method in developing CFC replacements.

A survey of refrigerant manufacturers and users determined that NIST's research has produced considerable benefits to industry. By comparing the industry benefits that were listed by the firms surveyed with the funding stream of NIST's alternative refrigerants research program, an internal rate of return for the program was calculated to be at least 433 percent, with an implied rate of return of approximately 21 percent, and a benefit-to-cost ratio of almost 4-to-1. These can be considered conservative estimates of the total net benefits for two main reasons. First, in the absence of NIST involvement in this area, heterogeneous sources of data for the physical properties of possible CFC replacements would have been developed, leading to uncertainty and transaction costs that could not be captured in the one-on-one industry surveys conducted for this assessment. These potential costs were avoided by NIST's development of standards that were available to all firms having a stake in the development and use of alternative refrigerants.

Second, NIST provided detailed physical properties data in a timely fashion so that the schedules laid out by the Montreal Protocol could be met by using new refrigerants that worked relatively efficiently compared to the refrigerants they replaced. It is possible that without NIST's research, moor poorly researched, less optimal refrigerants could have been adopted for use, with lowered energy efficiency as a result. The quantification of these energy cost savings were beyond the scope of this project.

# INTRODUCTION

## 1.1 NIST

The National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), was established by Congress in 1901 to support industry, commerce, scientific institutions, and all branches of government. During its existence, NIST has provided a wide range of products and services, including primary standards, reference materials, performance prediction and measurement methods, conformance tests and interoperability protocols, technical data certification, and measurement device calibration. NIST works with universities, government, private sector laboratories, standards developing bodies, and regulating bodies to establish and carry out its technical agenda.

NIST's research laboratories develop and deliver measurement techniques, test methods, standards, and other types of infrastructural technologies and services that provide a common language needed by industry in all stages of commerce – research, development, production, and marketing.

NIST is often called upon to contribute specialized research or technical advice to initiatives of national importance. The U.S. response to the international environmental problem of ozone depletion required such a contribution.

Historically, chemical compounds known as chlorofluorocarbons (CFCs) have been used extensively as aerosol propellants, refrigerants, solvents, and industrial foam blowing agents. However, these CFCs can break down and react with ozone found in the upper atmosphere, causing the ozone to decay.

Since 1987, the U.S. and other nations have forged international environmental protection agreements in an effort to replace CFCs with alternative, more environmentally neutral chemical compounds. NIST became involved in alternative refrigerant research in 1982 and has continued to support U.S. industry in its development and use of CFC replacements. The Physical and Chemical Properties Division of NIST's Chemical Science and Technology Laboratory has been the focal point for this effort.

## 1.2 NIST PHYSICAL AND CHEMICAL PROPERTIES DIVISION

The NIST Physical and Chemical Properties Division is part of the Chemical Science and Technology Laboratory (CSTL). The mission of CSTL is to provide the chemical measurement infrastructure to:

- Enhance U.S. industry's productivity and competitiveness
- Assure equity in trade
- Improve public health, safety, and environmental quality.

CSTL's goals are to:

- Establish CSTL as the pinnacle of the national traceability and international comparability structure for measurements in chemistry, chemical engineering and biotechnology, and provide the fundamental basis of the nation's measurement system
- Assure that U.S. industry has access to accurate and reliable data and predictive models to determine the chemical and physical properties of materials and processes
- Anticipate and address next-generation measurement needs of the nation by performing cutting-edge research.

The Physical and Chemical Properties Division itself has over 40 years of experience in the measurement and modeling of the thermophysical properties of fluids. The Division has laboratories in Boulder, Colorado, and Gaithersburg, Maryland, which include a broad array of experimental apparatus for performing measurements of the thermodynamic and transport properties of fluids and fluid mixtures across a wide range of temperatures and pressures.

The Division has been heavily involved with refrigerants for approximately ten years. Early work was performed in conjunction with the NIST Building Environment Division, which resulted in the development of early computer models of refrigerant behavior. In addition, research performed by Division members is regularly published in technical journals, and serves as a basis for the updating of tables and charts in reference volumes for the refrigeration industry.

Research in alternative refrigerants can be broken down into the following three areas:

- Studying how man-made chemicals affect the atmosphere. This is called "understanding the problem" by NIST personnel

- Studying the chemical and physical properties of alternative refrigerants
- Studying how to place chemicals in machines.

The latter two areas are referred to by NIST personnel as "solving the problem." Of the three areas, the Physical and Chemical Properties Division has been involved mainly in the second area, studying the *properties* of refrigerants.[1]

1 For an overview of the basic technology of refrigeration and the properties of various refrigerants, see Appendix A.

# 2. INDUSTRY OVERVIEW

## 2.1 BUSINESS ENVIRONMENT: THE MONTREAL PROTOCOL

The main reason for the refrigerant industry's switch from CFCs to alternative refrigerants was the issuance of the Montreal Protocol of 1987 and its subsequent amendments. The Protocol, formally known as "The Montreal Protocol on Substances that Deplete the Ozone Layer," is the primary international agreement providing for controls on the production and consumption of ozone-depleting substances, such as CFCs, halons, and methyl bromide. The Montreal Protocol was adopted under the 1985 Vienna Convention for the Protection of the Ozone Layer, and entered into force in 1989.

The Protocol outlines a phase-out period for substances such as CFCs. As of June 1994, 136 countries had signed the agreement, including practically every major industrialized country and most developing countries.

Every year, the Parties to the Protocol meet to review the terms of the agreement and decide if more actions are to be undertaken. In some cases, they update and amend the Protocol. Such amendments have been added in 1990 (London Amendment) and 1992 (Copenhagen Amendment). These amendments accelerated the phase-out of controlled substances, added new controls on other substances (such as HCFCs), and developed financial assistance programs for developing countries.

The main thrust of the original Protocol was to delineate a specific phase-out period for "controlled substances," i.e., CFCs and halons. Table 1, from Annex A of the Protocol, lists these substances and places them into two groups, I and II. Under Article 2 of the Protocol, a separate phase-out rate was established for each of the two groups. For Group I substances, the phase-out schedule calls for production and consumption levels to be capped at 100 percent of 1986 levels by 1990, with drops to 80 percent of the 1986 levels by 1994 and to 50 percent by 1999.

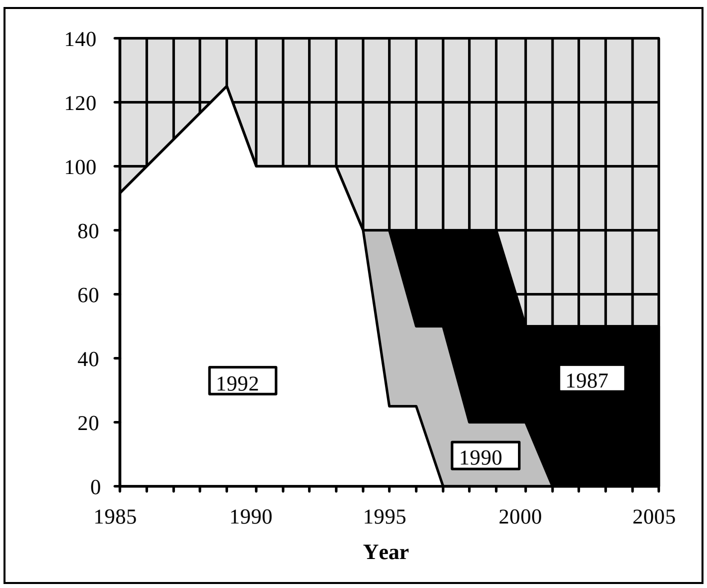
**Table 1: Controlled Substances**

| Group | Controlled Substance | | Ozone-Depleting Potential |
|---|---|---|---|
| Group I | $CFCl_3$ | (CFC-11) | 1.0 |
| | $CF_2Cl_2$ | (CFC-12) | 1.0 |
| | $C_2F_3Cl_3$ | (CFC-113) | 0.8 |
| | $C_2F_4Cl_2$ | (CFC-114) | 1.0 |
| | $C_2F_5Cl$ | (CFC-115) | 0.6 |
| Group II | $CF_2BrCl$ | (halon-1211) | 3.0 |
| | $CF_3Br$ | (halon-1301) | 10.0 |
| | $C_2F_4Br_2$ | (halon-2402) | TBD |

Source: Montreal Protocol, Annex A, 1987.

Further amendments to the Protocol in 1990 and 1992 called for acceleration of the phase-out process (see Figure 1), so that a total phase-out of CFC production would be achieved by January 1, 1996. Figure 1 shows how the initially longer phase-out period of the 1987 Protocol was changed from an eventual maintenance level of 50 percent of 1986 levels by 1999, to a complete phase-out by 2000, and finally to a complete phase-out by 1996.

**Figure 1: CFC Phase-Out Schedules**




Source: NIST documents

Although the thrust of the initial legislation was to force an end to CFC use and move parties to the Protocol toward less disruptive alternatives such as HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons), amendments such as the Copenhagen Amendment mandate further drops in production of HCFCs. The Copenhagen

Amendment requires a phase-out schedule for HCFC production similar to that for CFCs, over a longer time period, to end in 2030. The purpose is to allow parties to the Protocol to move off of CFCs by switching to HCFCs as an interim measure, but eventually to move off of HCFCs altogether and use HFCs for their refrigerant needs.

Other country-specific legislation is also significant in this area. The U.S. Clean Air Act amendments of 1990 enacted numerous changes in environmental laws, and mandated a stricter CFC phase-out rate than the London Amendment. The London Amendment called for a complete phase-out of CFCs by 2000, but the Clean Air Act moved this up to 1996 (the Copenhagen Amendment also calls for 1996 as the end of the phase-out period).

The European Community established a phase-out schedule of its own in 1994 which called for a faster phase-out period than the Copenhagen Amendment. The end year for the 1994 European Schedule was 1995.

## 2.2 INDUSTRY STRUCTURE

Generally, the alternative refrigerant industry consists of two types of firms: (1) refrigerant manufacturers that produce the alternative refrigerants, and (2) heating, ventilating, and air conditioning (HVAC) equipment manufacturers in whose machines the alternative refrigerants are used. These were the industry segments targeted for surveying.

### 2.2.1 Refrigerant Manufacturers

This industry grouping consists of firms that manufacture a wide range of chemicals, most of which are not related to alternative refrigerants. The six main manufacturers of alternative refrigerants are: DuPont, AlliedSignal, Elf Atochem, LaRoche, ICI, and Ausimont (see Table 2).

**Table 2: Fluorocarbon Capacity**

| Firm | Production Capacity (millions of lbs/year) |
|---|---|
| DuPont | 550.0 |
| AlliedSignal | 345.0 |
| Elf Atochem | 240.0 |
| LaRoche | 60.0 |
| ICI Americas | 40.0 |
| Ausimont USA | 25.0 |

Source: Chemical Marketing Reporter, January 30, 1995

Most of these firms have purchased multiple versions of the REFPROP program since its inception. Table 3 shows that DuPont leads in this category, with 20 versions of REFPROP (either copies of the original program or upgrades) in total. Next are AlliedSignal with 13 versions and Elf Atochem, with 10 versions, followed by ICI with six and LaRoche with three. Ausimont has not purchased any versions of REFPROP. These firms have also made use of the infrastructure research that NIST has performed in alternative refrigerants for their own development of proprietary refrigerant products. In addition, Dupont, AlliedSignal, Elf Atochem and LaRoche are the only firms still allowed to manufacture CFCs in the U.S.

**Table 3: REFPROP Purchases (Refrigerant Manufacturers)**

| Firm | REFPROP Purchases |
|---|---|
| DuPont | 20 |
| AlliedSignal | 13 |
| Elf Atochem | 10 |
| ICI Americas | 6 |
| LaRoche | 4 |
| Ausimont USA | 0 |

Source: NIST REFPROP Purchasers Database, 1996

Each of these firms markets its own brand of refrigerants. For example, DuPont's alternative refrigerants are sold under the Suva brand, while Elf Atochem sells the FX line (such as FX-10 and FX-56), and AlliedSignal markets AZ refrigerants (such as AZ-50).

The precise market shares of the alternative refrigerant market are not publicly available. However, since 1976, the fluorocarbon industry itself has voluntarily reported to the accounting firm of Grant Thornton LLP the amounts of fluorocarbons produced and sold annually, and this information is published in combined form.[2] Although the combined data do not allow for the calculation of market shares for each firm, the list of firms reporting gives a good approximation of the leaders of this industry. In addition to the firms listed above, five other firms or associations of firms provide fluorocarbon production and sales information to Grant Thornton. These firms are: Hoechst AG (Germany), the Japan Fluorocarbon Manufacturers Association (Japan), Rhône-Poulenc Chemicals, Ltd. (U.K.), Société des Industries Chimiques du Nord de la Grèce, S.A. (Greece), and Solvay S.A. (Belgium).

2 "Production, Sales and Atmospheric Release of Fluorocarbons Through 1994," AFEAS (Alternative Fluorocarbons Environmental Acceptability Study), Washington D.C., October 1995.

Collectively, this industry is a primary beneficiary of the research that NIST has done in alternative refrigerants. The research team decided to survey the top five firms from Table 3 for the benefits of NIST research. The survey candidates were chosen because they have relatively high levels of fluorocarbon production capacity, they have all purchased copies of the REFPROP program, and they all are either U.S. firms or have a strong U.S. market presence.

### 2.2.2 HVAC Equipment Manufacturers

Firms in this industry are primarily engaged in the manufacturing of commercial and industrial refrigeration and air-conditioning equipment. Such equipment is used at the local supermarket, in office buildings, stores, shopping malls, hospitals, and homes.

Major firms in this industry include Carrier, Trane, and York. Their workforce levels and sales figures are listed in Table 4. Through the 1980s, the U.S. HVAC equipment industry structure changed only slightly, with the number of firms increasing from 730 in 1982 to 736 in 1987.[3] The largest seven of them held 72 percent market share in the U.S.

**Table 4: Major Industrial HVAC Equipment Manufacturers**

| Firm | Workforce | Sales ($B) |
|---|---|---|
| Carrier | 28,000 | $3.80 |
| Trane | 13,000 | $1.42 |
| York International | 11,500 | $1.60 |

Source: Encyclopedia of American Industries, 1994

There are many other smaller HVAC equipment manufacturers represented among REFPROP purchasers. The number of REFPROP purchases (either copies of the original program or upgrades) by the larger equipment manufacturers is shown in Table 5.

**Table 5: REFPROP Purchases (HVAC Equipment Manufacturers)**

| Firm | REFPROP Purchases |
|---|---|
| Copeland | 8 |
| York | 7 |
| Carrier | 5 |
| Trane | 5 |
| Thermo-King | 1 |
| Tecumseh | 1 |

Source: NIST REFPROP Purchasers Database, 1996

3 Hillstrom, Kevin (ed.), *Encyclopedia of American Industries, Volume 1: Manufacturing Industries*, p. 1005, Gale Research, Inc., New York, 1994.

Representatives from the six HVAC equipment manufacturing firms listed in Table 5 were contacted and interviewed in order to provide cost and savings information relevant to the economic analysis conducted by the research team.

## 2.3 ECONOMIC IMPORTANCE OF NIST'S ROLE IN THE DEVELOPMENT OF ALTERNATIVE REFRIGERANTS

NIST's involvement in technology development and diffusion projects is predicated on the existence of market failures – barriers to the appropriate level and timing of investment in technology.[4] NIST becomes involved in specific technology initiatives because of these routine barriers to technology development and diffusion.

One such barrier arises from the very nature of NIST's expertise in the development and maintenance of measurement standards, evaluated data, and definitive methodologies for determining quality. The technology that derives from NIST's expertise is often most effective only when shared widely. Due to the implicit "publicness" of such technology it receives little private sector support. While important to firms' research, and often to their ability to market "compatible" goods and services, the anticipated ability to capture sufficient returns on investments acts as a strong disincentive to developing these technologies. Alternative sources of these "infrastructure technologies" are often sought by industry (e.g., through research joint ventures, cooperative research and development agreements, and other forms of collaborative research). For such reasons, NIST laboratories are often called upon to participate in technology initiatives of national importance.

NIST involvement in alternative refrigerants research demonstrates the complex and fundamental role that the NIST laboratories often play in facilitating technological progress. Market failures commonly arise in connection with environmental problems. Generally speaking, these problems arise because actions taken by individuals (or organizations) have unintended adverse spillover effects on others. *Global* environmental problems are further complicated by the fact that the individuals involved often are scattered throughout many nations. International cooperation is required to solve such problems.[5]

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4 See Gregory Tassey, *The Economics of R&D Policy* (New York: Quorum Books, forthcoming 1997); and *Technology and Economic Growth: Implications for Federal Policy*, National Institute of Standards and Technology Planning Report 95-3, October 1995.

5 *Economic Report of the President*, U.S. Government Printing Office, February 6, 1990, (p. 207).

Suspected ozone depletion of the upper layer of the earth's atmosphere is such a problem. CFCs have long been a concern for U.S. environmental policy makers. In 1978, the U.S. banned the use of CFCs as aerosol propellants, a use for which substitutes were readily available. However, the use of CFCs for other applications, such as automotive and residential air-conditioning systems, refrigerators, and fire extinguishers, continued to grow.

Starting in 1982, NIST's efforts focused on characterizing the chemical properties of alternative refrigerants and how these refrigerants performed when mixed with other refrigerants. These efforts merged with private sector and university efforts to address potentially very costly economic disruptions.[6] According to interviews with industry and university researchers, NIST served numerous functions that were important to the timely, efficient implementation of the international agreement to phase out CFCs. That is, without NIST's participation, it is unlikely that the market alone would have been able to accomplish this important objective nearly as well. Our economic rate-of-return calculations (presented in chapter 5) indicate that NIST's participation afforded an economical solution to the problems of transitioning from ozone-depleting refrigerants.

NIST's participation also affected the *timeliness* of the private sector's reaction to the Montreal Protocol's phase-out plan. According to Congressional testimony, NIST efforts were very important in this respect:

> Under normal circumstances our industry could do the necessary research and testing without any assistance, with equipment manufacturers and refrigerant producers working together. But there is too much to be done in a short time, to test and prove all of the candidate refrigerants, select the most suitable and efficient ones for various applications, design and test new equipment, and retool for production. The process takes time – and money. Depending on the type of equipment, normally it would take 5-10 years, even after a refrigerant is available, to make appropriate design changes and thoroughly field test a new product before it is introduced commercially.[7]

6 The economic costs of phasing out CFCs were estimated in the billions of dollars and these estimates were based on assumptions concerning the availability of substitute technologies. (*See Economic Report of the President*, U.S. Government Printing Office, February 6, 1990, p. 210). Industry interviews confirm that NIST's alternative refrigerants research was an important part of helping make these alternatives feasible.

7 Testimony of Arnold Braswell, President of the Air-Conditioning and Refrigeration Institute (ARI), Hearing before the Subcommittee on Oversight and Investigations of the Committee on Energy and Commerce, House of Representatives, 101st Congress, First Session, Y4.En2/3:101-87, May 15, 1989.

It is also important to understand NIST's role in the system-like complex that is increasingly typical of technological progress. Very often government, private sector, and university research efforts pursue complementary lines of work that result in technological progress that would not occur if these cooperative efforts had not taken place.[8] NIST's alternative refrigerant research provides a good example of this phenomenon. Industry representatives postulated that while the majority of work necessary to effect a transition to new CFC refrigerants had to be performed by industry, government supported research would play a critical role in the initial stages.[9]

NIST's alternative refrigerants research also supports the basic research facets of technology development typically undertaken by universities. University researchers recognize NIST's unique ability to provide consistent data on a wide range of fluids in a timely manner,[10] view this work as *complementary* to their own research,[11] and use it as a foundation for further research.[12] Mark Menzer of ARI remarked:

> We had been using CFCs forever, and now we have to get rid of them on short order. We knew we would need data, high-quality data, since small design errors based on the data can lead to big miscalculations about a cooling unit's efficiency and cost. We have used NIST data and the REFPROP program as the standard. We have used this information to make important decisions. Without NIST we would have gotten less detailed data, which would have meant a lot more expensive, time-consuming engineering work to produce hardware. It would have cost us millions more.[13]

Menzer also added that without NIST and REFPROP serving as a common source of data for the industry, each company probably would make different choices about refrigerants, a scenario that would lead to a technical "Tower of Babel" for the maintenance and repair community.

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8 See Link, Albert N., and Gregory Tassey, *Strategies for Technology-based Competition: Meeting the New Global Challenge* (Lexington, Massachusetts: Lexington Books, D. C. Heath, 1987) and Gregory Tassey, *Economics of R&D Policy*, Quorum Books, 1997.

9 Braswell, ibid.

10 Interview with representative of the Air Conditioning & Refrigeration Center, University of Illinois, May 9, 1997.

11 Interview with representative of the College of Engineering, University of Idaho, May 19, 1997.

12 Interview with representative of the Center for Environmental Energy Engineering, University of Maryland, May 16, 1997.

13 Cited in the "Work by the NIST Physical and Chemical Properties Division on Alternative Refrigerants" data package provided by NIST.

Finally, NIST's alternative refrigerants program appears to offer an example of another important "market-perfecting" function: *reducing transaction costs* through its dissemination of reliable data (and/or evaluation methodologies). Industry recognizes NIST's technical capabilities to cover a wide range of chemical properties with a high degree of accuracy. According to one industry advocate of NIST's involvement in refrigerants research, "NIST's research would become the industry standard ... and would reside in the public domain, allowing for access by a wide range of users."[14] This, in turn would reduce total costs associated with duplicative private sector research as well as reduce transaction costs associated with effectively communicating such data to the market. According to another chemical industry representative, the alternative refrigerants data provided by NIST were key in helping industry design equipment to handle new fluorocarbons.[15] Equipment designers, too, rely on NIST as an authoritative source of information. Prior to the availability of REFPROP, refrigeration equipment manufacturers relied upon technical information from chemical manufacturers but were subject to the risks and costs of data variability among chemical providers, especially for newer refrigerants.

## 2.4 NIST ALTERNATIVE REFRIGERANTS PROGRAM MILESTONES

While NIST considered research into refrigerants as far back as 1982, NIST did not establish a formal research program into alternative refrigerants until 1987, after both the passage of the Montreal Protocol and the publication of the McLinden and Didion paper ("Quest for Alternatives"). NBS Technical Note 1226 ("Application of a Hard-Sphere Equation of State to Refrigerants and Refrigerant Mixtures") by Morrison and McLinden in 1986 provided the initial basis for the REFPROP program, first released in 1990 and subsequently updated four more times. Major milestones in NIST's alternative refrigerants program are listed in Table 6.

14 Letter from Joseph Steed, Environmental Manager of DuPont to Stephen Anderson, Senior Economist of EPA, March 24, 1988.

15 Letter from Donald Bivens of DuPont to Richard Kayser of NIST, May 12, 1994.

## Table 6: Program Milestones

| Year | Events | Legislation | Publication | Release of Data | Contract/ Agreement | Internal Event |
|---|---|---|---|---|---|---|
| 1982 | NIST begins early work on looking at alternative refrigerants. | | | | | • |
| 1986 | NBS Technical Note 1226 published – formed the initial basis for the REFPROP program. | | • | | | |
| 1987 | Montreal Protocol signed. | • | | | | |
| | "Quest for Alternatives" by Mark McLinden and David Didion published in the ASHRAE Journal. | | • | | | |
| 1989 | NIST's Long-Range Plan on Alternative Refrigerants completed. | | | | | • |
| | Definitive publication on the properties of R134 and R123. | | • | | | |
| | First mass-mailing of NIST technical results completed. | | | • | | |
| 1990 | London Amendment to Montreal Protocol signed. | • | | | | |
| | Clean Air Act amendments passed. | • | | | | |
| | Version 1.0 of REFPROP released (01/90). | | | • | | |
| | Air-Conditioning & Refrigeration Institute (ARI) signs agreement to distribute REFPROP to its member companies. | | | | • | |
| 1991 | Version 2.0 of REFPROP released (02/91). | | | • | | |
| | Version 3.0 of REFPROP released (12/91). | | | • | | |
| 1992 | Copenhagen Amendment to Montreal Protocol signed. | • | | | | |
| | Work begun for the Air Conditioning & Refrigeration Technology Institute (ARTI). | | | | • | |
| | ARTI adopts REFPROP as the source for thermophysical/thermodynamic properties for its Evaluation Program. | | | | • | |
| 1993 | First contract for ARTI completed by NIST. | | | | • | |
| | ASHRAE Handbook of Fundamentals revised. | | • | | | |
| | Version 4.0 of REFPROP released (11/93). | | | • | | |
| 1994 | Second contract for ARTI completed by NIST. | | | | • | |
| 1995 | CRC Handbook for Alternative Refrigerant Analysis published. | | • | | | |
| 1996 | Version 5.0 of REFPROP released (02/96). | | | • | | |
| | Third contract for ARTI completed by NIST. | | | | • | |

# 3. ECONOMIC FRAMEWORK

In this chapter, we explain the framework for capturing and quantifying the economic effects of NIST's alternative refrigerants research. The framework entails the identification of key technical outputs, the development of an approach to ascertaining quantitative estimates of the economic value of these technical outputs, and identification of the relevant survey population.

## 3.1 ALTERNATIVE REFRIGERANT PROGRAM OUTPUTS

NIST's research into alternative refrigerants has produced technical outputs in the following five areas:

- Extensive measurements and numerous high-accuracy models for the thermodynamic and transport properties of pure alternative refrigerants and refrigerant mixtures, resulting in numerous publications in the archival literature

- An extensive update of the tables and charts in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook of Fundamentals – a reference volume distributed to over 50,000 practicing engineers worldwide. This has been referred to as "the Bible" of the industry by a number of independent sources

- Participation and leadership of international forums charged with assessing the state of the art and arriving at international standards for refrigerant properties (e.g., the United Nations Environment Programme, International Energy Agency Annex 18)

- A comprehensive analytical database for alternative refrigerants published by CRC Press

- REFPROP, an electronic database which calculates the properties of 41 pure refrigerants and mixtures with as many as five components. REFPROP has become the de facto standard for the refrigeration industry. ARI (the Air-Conditioning and Refrigeration Institute) and the Electric Power Research Institute adopted it as the primary source of properties data for their Alternative Refrigerants Evaluation Program. The NIST Standard Reference Data Program has sold over 500 copies of REFPROP since the first version came out in January 1990.

NIST researchers have communicated the results of much of this research in over 140 published articles and papers over the period 1986-1996.[16] Of the five areas listed above, key NIST personnel indicated that the most important outputs were the measurements and models, the update to the ASHRAE Handbook, and the REFPROP program.

## 3.2 METHODOLOGY FOR COLLECTING ECONOMIC BENEFIT DATA

To estimate the economic impact of NIST's research program in alternative refrigerants we utilized an approach adopted from evaluations of other public investments in infratechnology.[17] Specifically, research costs were compared to an estimate of the benefits received by industry using a hypothetical, counterfactual experiment. The experiment assumed that the first-level economic benefits associated with the NIST-conducted research program on alternative refrigerants could be approximated in terms of the additional costs that industry would have incurred in the absence of the NIST-conducted research. In other words, these are the costs avoided by industry due to the existence of the NIST-conducted research program and the availability of information or products from that program.

The counterfactual experiment is used because this case study lacks comparable baseline observations. In other words, it is not the case that some firms in the refrigerant industry, broadly defined, relied upon research results emanating from research conducted at NIST and others did not. If that were so, then one could compare the production-related efficiency between the two groups to ascertain a first-order measure of the added value of the NIST-conducted research. As discussed above, industry was forced, as a result of the Montreal Protocol, into a situation where it had to respond to mandated guidelines in a short period of time. As such, firms in the industry relied upon the extant knowledge base at NIST since no alternative knowledge base existed at that time.

Previous experience in gathering information related to the economic benefits associated with NIST research suggests that the most efficient, and therefore presumably most accurate,

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16 "Publications Concerning Alternative Refrigerants, 1986-1995," Physical and Chemical Properties Division, National Institute of Standards and Technology, Gaithersburg, Maryland and Boulder, Colorado (last updated 8/16/96).

17 See Gregory Tassey, *The Economics of R&D Policy* (New York, Quorum Books, 1997); Albert N. Link, *Evaluating Public Sector Research and Development* (Praeger, New York, 1996); and Gregory Tassey, *Rates of Return from Investments in Technology Infrastructure*, NIST Planning Report 96-3, June 1996.

means to collect data is through semi-structured, interactive telephone interviews. Hence, we chose that mode of data collection for this case study.

## 3.3 SURVEY POPULATION

Two groups of potential first-level users of NIST's research were identified with the assistance of individuals within the Physical and Chemical Properties Division of the Chemical Science and Technology Laboratory at NIST. The first group consisted of the five major domestic manufacturers of alternative refrigerants: DuPont, Elf Atochem, ICI Americas, AlliedSignal, and LaRoche. This group of five refrigerant manufacturers represents about 90 percent of the industry, as approximated in terms of production capacity. The second group consisted of the six major domestic users of refrigerants: York International, Thermo-King, Copeland, Tecumseh, Carrier, and Trane. This group of six manufacturers represents over 70 percent of the industry, as approximated in terms of manpower levels. However, because no information was available as to how representative the group of eleven companies is in terms of benefits received, we did not attempt to extrapolate benefits from the sample of eleven companies to the entire industry.[18]

18 Based upon our interviews (discussed below), it is very clear that users of REFPROP cannot be characterized by size, market share, or other obvious structural features. Thus, there is no sound methodological foundation for extrapolating our sample results to the total population. While such an extrapolation is mathematically possible, because of the diversity of REFPROP users, the results would be highly speculative.

# 4. INDUSTRY SURVEY

## 4.1 SURVEY RESULTS

Separate interview guides were prepared for the five manufacturers of refrigerants and six users of refrigerants. Previous experience by the TASC team in collecting economic benefit data associated with the use of infratechnology research dictated that these interview guides only include broad topics of interest. Through verbal interactions with the industry respondents, certain areas would be explored more heavily than others as the situation dictated.

Background areas that were discussed with both the manufacturers and the users of alternative refrigerants focused on the extent to which they anticipated the Montreal Protocol, their in-house research programs, and their familiarity with REFPROP. As discussed in the following sections, more specific questions were addressed to manufacturers and to users. Each company that was interviewed was asked a common question: "Absent NIST's activities, what would your estimate be of the additional man-years of research you would have needed in order to achieve your current level of technical knowledge or ability, and how would these man-years of research have been allocated over time?" Follow-up questions focused on the value of a fully-burdened man-year of research and the value of supporting research equipment.[19]

### 4.1.1 Manufacturers of Alternative Refrigerants

The five manufacturers of refrigerants anticipated the Montreal Protocol and were, generally, supportive of it for environmental and health reasons. The larger companies, in the absence of NIST's materials properties database, would likely have responded to the protocol by hiring additional research scientists and engineers to attempt to provide the materials characterization and analysis needed by their alternative refrigerant research programs being conducted in-house or through participation in research consortia. The smaller companies among these five reported that they would have relied on others' (in the industry) research, and in the interim looked for alternative uses of the HCFCs they produced.[20]

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19 More precisely, each respondent was asked the current value of a fully-burdened man-year ($1996 responses) and the rate at which such expenses had increased over time. Given that annual growth rate, the person-year cost estimate was deflated to arrive at nominal annual values.

20 Recall that HCFCs were not phased out; additional controls were placed upon these substances.

All of the manufacturers were aware of the research at NIST, and four of the five manufacturers purchased NIST's REFPROP when it was first available in 1990 (the fifth respondent thought that his company first purchased REFPROP in 1992). All used the most recent version of REFPROP for verifying properties of new compounds, either to be made by the company for general sale or to be made by the company for a specific customer. Interestingly, every respondent noted that REFPROP was easy to use and that minimal learning costs ("pull costs") were associated with incorporating the software into production.

Regarding the calculation of new benefits from NIST's research program, each of the five firms responded in terms of the additional man-years of research effort – absent the NIST-conducted research program – that would have been needed since the Montreal Protocol to achieve the same level of technical knowledge on alternative refrigerants that they have now. Each respondent was asked the current value of a fully-burdened man-year of research effort and this was then imputed to the annual estimates of additional research needs, by company. To these annual totals, by company, the respondents' estimates of the value of additional equipment were added (additional equipment needs were generally minimal compared to additional research personnel needs). The annual benefits to this group of five manufacturers are shown in Table 7. It is notable that each company's estimated annual benefits began as early as 1989, shortly after the Montreal Protocol went into effect.[21]

**Table 7: Net Economic Benefits to Refrigerant Manufacturers**

| Year | Net Benefits ($000s) |
|---|---|
| 1989 | $2,090.2 |
| 1990 | 1,125.1 |
| 1991 | 1,107.4 |
| 1992 | 536.6 |
| 1993 | 552.4 |
| 1994 | 569.1 |
| 1995 | 586.3 |
| 1996 | 603.9 |

Source: Industry survey

21 Some companies reported in the interviews that benefits could have begun in 1988, but given that they were not sure of this, the more conservative date of 1989 was used in the analyses that follow.

The quantitative estimates in Table 7 are viewed as net economic benefits associated with NIST's alternative refrigerant program in the sense that manufacturers of refrigerants would have expended these additional resources to reach their current level of technical expertise in the absence of NIST's research programs.

### 4.1.2 Users of Alternative Refrigerants

The six users of refrigerants produced a variety of heating, cooling, and other refrigerant equipment. As a group, they, like the manufacturers, anticipated the Montreal Protocol, and like the manufacturers they did conduct investigations (which they call "component development" or "advanced development" rather than "research and development") into equipment efficiencies and alternative lubricants needed in anticipation of new refrigerants. Accordingly, it was not unexpected to find that these companies were less familiar with NIST's underlying research program into alternative refrigerants than the refrigerant manufacturers.

However, each company was familiar with NIST's REFPROP. REFPROP is important to refrigerant users because it assists them in verifying the properties of alternative refrigerants, especially new ones. As one respondent noted, were REFPROP not available:

> We would have been at the mercy of the [refrigerant] manufacturers to meet deadlines...this would mean that to deliver equipment that met Montreal Protocol specifications we would have been less reliable.

While these refrigerant users were less complimentary about the ease of use of REFPROP than the manufacturers, they were of the opinion that it did add value to their ongoing operations. Noteworthy are their comments that REFPROP is "very cumbersome to use" or "not that user-friendly."

The refrigerant users were asked a more constrained version of the counterfactual question, "In the absence of NIST…" Specifically, each interviewee was asked the additional man-years of effort that would have been needed, absent NIST's REFPROP, for them to achieve the same level of product reliability as they currently have. Five of the six companies were comfortable answering this question; the sixth company was not comfortable offering even a ranged response, although this company did report that it did receive positive benefits.[22] The

22 For estimation purposes, we imputed the median dollar response from the other companies.

additional man-years of effort reported by the interviewees were generally described in terms of additional quality control engineers. As above, each man-year was valued in terms of the company's cost of a fully-burdened man-year and when appropriate, additional equipment costs were also added to the net benefits estimated in Table 8.

**Table 8: Net Economic Benefits to Refrigerant Users**

| Year | Net Benefits ($000s) |
|---|---|
| 1988 | n/a |
| 1989 | n/a |
| 1990 | $2,342.5[23] |
| 1991 | 550.6 |
| 1992 | 534.8 |
| 1993 | 519.2 |
| 1994 | 503.9 |
| 1995 | 489.2 |
| 1996 | 475.0 |

Source: Industry survey

23 This estimate included a sizable one-time additional equipment cost by one user.

# 5. ECONOMIC ANALYSIS

## 5.1 NIST ANNUAL EXPENDITURES

Table 9 summarizes all expenditures associated with research conducted at NIST that are relevant to this study. The research funded directly by NIST is reported in the second column of the table, and the relevant other agency research expenditures are reported in the third column of the table. The total in column four is compared to estimated industry benefits in the economic analysis section of the report.

**Table 9: Expenditures Associated with Alternative Refrigerants Research Conducted at NIST ($000s)**

| Year | NIST-Financed Research Expenditures[24] | Other Agency-Financed Research Expenditures[25] | Total |
|---|---|---|---|
| 1987 | $68 | $0 | $68 |
| 1988 | 75 | 0 | 75 |
| 1989 | 250 | 95 | 345 |
| 1990 | 225 | 265 | 490 |
| 1991 | 175 | 280 | 455 |
| 1992 | 275 | 555 | 830 |
| 1993 | 275 | 685 | 960 |
| 1994 | 375 | 770 | 1,145 |
| 1995 | 475 | 900 | 1,375 |
| 1996 | 475 | 400 | 875 |
| Total | 2,668 | 3,950 | 6,618 |

## 5.2 ANALYSIS OF COST AND BENEFIT DATA

Table 10 shows total expenditures for research conducted at NIST on alternative refrigerants and on REFPROP-related information, by year, along with industry reported benefits.

24 1987 and 1988 NIST expenditures were estimated by NIST personnel.

25 Other agency costs include research conducted at NIST for government and private agencies that is directly relevant to NIST's research agenda in support of industry needs. These agencies included the Department of Energy, the Air Conditioning and Refrigeration Technology Institute, the Environmental Protection Agency, the Electric Power Research Institute, the American Society of Heating, Refrigeration, and Air Conditioning Engineers, E.I. Dupont de Nemours, Inc., and ICI Americas.

Expenditure data are derived from Table 9 and the benefit data are obtained by combining Table 7 and Table 8.

**Table 10: Net Industry Benefits from NIST-Conducted Research ($000s)**

| Year | Total Expenditures on Research Conducted at NIST[26] | Total Benefits Reported by Industry | Net Industry Benefits |
|---|---|---|---|
| 1987 | $68.0 | $0.0 | ($68.0) |
| 1988 | 75.0 | 0.0 | (75.0) |
| 1989 | 345.0 | 2,090.2 | 1,745.2 |
| 1990 | 490.0 | 3,467.6 | 2,977.6 |
| 1991 | 455.0 | 1,658.0 | 1,203.0 |
| 1992 | 830.0 | 1,071.4 | 241.4 |
| 1993 | 960.0 | 1,071.6 | 111.6 |
| 1994 | n/a | 1,073.0 | 1,073.0 |
| 1995 | n/a | 1,075.5 | 1,075.5 |
| 1996 | n/a | 1,078.9 | 1,078.9 |

It is important to note that no NIST-related expenditures are included in this summary table for the years 1994, 1995, and 1996. These data were reported above in Table 9. They are excluded from the economic rate of return calculations because the research that resulted from these expenditures has not yet had time to be included in a version of REFPROP from which industry would benefit. Version 4.0 of REFPROP was released in November 1993 and Version 5.0 was released only in February 1996.

It is quite common in analyses of economic benefits resulting from public sector research to experience such lags in the conduct of research and the benefits that are received by industry. Alternatively, expenditures for the years 1994, 1995, and 1996 could have been included in the rate of return analyses, but then anticipated benefits to industry in the years 1997, 1998, 1999, and likely 2000 would need to have been included. We rejected this forecasting approach in favor of what we believed to be a rate of return analysis that was based on more accurate data.

## 5.3 INTERNAL RATE OF RETURN

By definition, the internal rate of return is the value of the discount rate, i, that equates the present value (PV) of a net benefit stream to zero:

26 Expenditure data for 1994, 1995, and 1996 are not applicable for the analyses in this section of the report.

$$PV = [(B_0-C_0)/(1+i)^0] + ... + [(B_n-C_n)/(1+i)^n] = 0$$

where $(B_n-C_n)$ represents net benefits and n represents the number of time periods.

Based on the net benefit data in Table 10, the calculated value of i for which PV=0 is 4.33 (rounded), implying an internal rate of return to NIST conducted research in alternative refrigerants of 433 percent.

It should be noted that when PV=0, B/C=1. PV can be rewritten as:

$$PV = [\Sigma_{t=0 \text{ to } n} B_t/(1+r)^t] - [\Sigma_{t=0 \text{ to } n} C_t/(1+r)^t]$$

where r is the theoretical discount rate used to reference future benefits and costs to present value. When PV=0, it follows that:

$$\Sigma_{t=0 \text{ to } n} B_t/(1+r)^t = \Sigma_{t=0 \text{ to } n} C_t/(1+r)^t$$

or that the present value of benefits equals the present value of costs, or B/C=1.

If the value of r used is the opportunity cost of funds invested by NIST and other agencies, the PV, as defined above, reflects what finance text books refer to as “net present value” and thus reflects the so-called profits of the investment. The internal rate of return estimate of 433 percent means that 4.33 is the value of the discount rate that equates the present value of benefits to the present value of costs. Thus, if the opportunity cost of funds r is less than 4.33, the internal rate of return, then the present value is positive and the project is a profitable one. Economists and policy makers generally use internal rate of return measures for on-going or completed public-sector research projects to estimate what is referred to as the social rate of return. As such, one can infer from the 433 percent value calculated from the data in Table 10 that if 433 percent is above NIST’s hurdle rate or generally accepted expected rate of return then NIST’s services are, from a social perspective, worthwhile.[27]

## 5.4 IMPLIED RATE OF RETURN

It is not uncommon to interpret an internal rate of return measure as an annual yield similar to that earned on, say, a bank deposit. Such a direct comparison is, however, incorrect.

27 In the analyses that follow, we approximate NIST’s hurdle rate as the opportunity cost of obtaining public funds, namely the long-term nominal rate of interest.

The return earned on a bank deposit is a compounded rate of return. One invests, say \$100, and then earns interest on that \$100 each year plus interest on the interest. That is not the case in an R&D project, in general, or in the case of NIST's investments in alternative refrigerants research, in particular.

Under an alternative set of assumptions, one can calculate an implied rate of return from the data in Table 11, but this rate of return is not the same as the internal rate of return and should not be interpreted as a social rate of return.

If all costs in Table 10 are referenced to 1987 using a discount rate equal to the sum of the Office of Management and Budget's recommended real rate of 7 percent plus the actual rate of inflation that occurred in each previous year as measured by the GDP Price Index (chain-type weights), then the present value of NIST resource investments in alternative refrigerants is \$2.6 million (rounded).[28] If all benefits in Table 10 are referenced forward to 1996 using the same rates, the current value of all measured industrial economic benefits is \$14.2 million (rounded).

The implied annual compounded rate of return that corresponds to an initial investment of \$2.6 million in 1987 growing to \$14.2 million by the end of the 1996 can be calculated. Such a compounded rate of return, x, equals 20.7 percent based upon the following relationship:

$$\$2.6\ (1+x)^9=\$14.2$$

## 5.5 BENEFIT-TO-COST RATIO

The calculation of a benefit-to-cost ratio (B/C) for alternative refrigerant research is based upon the following formula:

$$B/C = [\Sigma_{t=0 \text{ to } n}\ B_t/(1+r)^t] \ / \ [\Sigma_{t=0 \text{ to } n}\ C_t/(1+r)^t]$$

As the formula shows, all costs and all benefits are discounted to the base period, which is 1987. Using a nominal discount rate equal to 7 percent plus the prevailing rate of inflation, the

28 See Office of Management and Budget, "Memorandum for Heads of Executive Departments and Establishments, Circular No. A-94," Washington, DC, October 29, 1992.

present value of benefits is $10.1 million (rounded) compared to the previously calculated present value of costs of $2.6 million. Thus, the calculated benefit-to-cost ratio is 3.9-to-1.[29]

29 In general, we expect research with a high social rate of return to be associated with a high benefit-to-cost ratio. In this case, due to the way in which the two metrics are calculated, the benefit and cost data yield a very large net benefits estimate in the first two years that net benefits are positive. Hence, these values need to be heavily discounted to yield a present value of net benefits equal to zero (per the IRR formula). This net benefit profile does not, however, affect the calculation of a benefit-to-cost ratio.

## 6. CONCLUSIONS

The preceding analysis indicates that significant economic benefits have resulted from NIST's alternative refrigerants research. This research has resulted in a social rate of return (SRR) of 433 percent, an implied rate of return of approximately 21 percent, and a benefit-to-cost ratio (B/C) of almost 4-to-1. An SRR of 433 percent represents a relatively high economic impact as compared with other similarly evaluated NIST projects.[30]

These economic impact calculations represent a conservative estimate of the total economic impact of NIST's alternative refrigerants research because they represent only first-order economic benefits. Specifically, we construed the benefits from NIST's alternative refrigerants research as being the difference between actual NIST research costs and the costs that would have been incurred by industry in the absence of NIST efforts. While the social rate of return to NIST's alternative refrigerants program is substantial, it is interpreted as a lower bound estimate of all the benefits that have accrued from NIST's investments.

Our research and interviews suggest that there are undoubtedly other substantial benefits. First, transaction cost savings could be substantial. That is, in the absence of reliable data concerning the properties of alternative refrigerant compounds, firms designing refrigeration equipment would be forced to rely on less comprehensive, less accurate, and more heterogeneous properties data furnished by individual chemical producers. The costs of evaluating that data could be significant, especially for new refrigerants, and would conceivably be incurred repeatedly by numerous equipment designers, who doubted the performance claims of suppliers. The estimation of these costs could add substantially to the benefit stream emanating from NIST's investments while affecting NIST's costs only modestly, if at all.

A second source of additional economic benefits from NIST's alternative refrigerants research could be ascertained from estimates of energy cost efficiencies that would not have occurred absent NIST's efforts. That is, given the deadlines for CFC replacements imposed by international agreements, in the absence of NIST's efforts it is certainly possible that more poorly researched, less optimal refrigerants would have been adopted and energy efficiency of equipment utilizing these inferior chemicals would have been degraded.

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30 See Gregory Tassey, *Rates of Return from Investments in Technology Infrastructure*, NIST Planning Report 96-3, June 1996.

A third benefit resulting from NIST's involvement in this research was addressed earlier in this report: NIST provided a degree of standardization of results that might possibly not have existed had alternative refrigerant development been left to industry alone. This standardization served to reduce uncertainty about refrigerant properties, and allowed refrigerant manufacturers and users to develop new products with the knowledge that the underlying data upon which they were basing their product designs was solid.

A final, important benefit of NIST's research program is the avoidance of burdensome regulations and taxes that could have been imposed upon the refrigerant producing industry had NIST's research been performed for and funded by the industry itself. Congressional testimony from the late 1980s indicates quite clearly that many interest groups viewed the refrigerant manufacturers as the root cause of the ozone depletion problem and thus did not embrace the prospect of these same manufacturers profiting from the government-mandated increase in demand for alternative refrigerants. NIST's involvement as a neutral third-party served to defuse this politically charged issue by removing from consideration the perceived exploitation of the market response to the Montreal Protocol by these manufacturers.

While methodological difficulties and resource constraints have prevented the estimation of the overall social benefits from NIST's alternative refrigerants research, we have every reason to believe additional net benefits could be estimated and that the return to NIST investments would thereby surpass the estimates calculated above.

# APPENDIX A
# TECHNICAL OVERVIEW OF
# ALTERNATIVE REFRIGERANTS

The alternative refrigerants research that has been performed at NIST over the past decade is concerned with determining the physical properties of refrigerants. This appendix gives a brief overview of the technological issues that bear upon this research.

## A.1 REFRIGERATION

Refrigeration is a process by which a substance is cooled below the temperature of its surroundings. Objects can be cooled as well as areas and spaces. The type of refrigeration related to the work at hand is referred to as mechanical (as opposed to natural) refrigeration, and it came into use during the twentieth century.[31]

For mechanical refrigeration to work, a number of components are required. The vapor-compression cycle of refrigeration requires the use of a compressor, a condenser, a storage tank, a throttling valve, and an evaporator as shown in the cycle begins with the liquid refrigerant boiling at a low temperature in the evaporator. This produces the desired cooling effect. The refrigerant is then sent through the compressor, which raises its pressure and temperature. It then moves to the condenser, where its heat is released to the environment, and then through the throttling valve to the evaporator where its pressure and temperature drop. At this point the cycle begins again. In Figure A-1, Q represents the flow of heat through the system. The conduit for the heat exchange is the refrigerant itself. Heat energy from the substance or area that is to be cooled is transferred to the refrigerant, which then transfers the heat to the outside environment. Energy is moved from one place to another.[32]

In order for a refrigerant to be effective, it must satisfy certain criteria, outlined in Table A-1.[33] Not every refrigerant will satisfy every criterion. In deciding upon a particular refrigerant to use, the range of criteria must be taken into account. For instance, a refrigerant that has acceptable thermodynamic properties might be extremely toxic to humans, while one that is satisfactory from a thermodynamic standpoint and which is non-toxic might be unstable and break down inside the refrigeration machinery.

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31 *McGraw-Hill Encyclopedia of Science & Technology*, 7th Edition, vol. 15, pp. 256-263, McGraw-Hill, Inc., New York, 1992.

32 Considine, Douglas M., ed., *Van Nostrand's Scientific Encyclopedia*, 8th Edition, pp. 2663-2666, Van Nostrand Reinhold, New York, 1995.

33 Didion, David A., and McLinden, Mark O., "Quest for Alternatives," *ASHRAE Journal*, p. 35, December 1987.

**Figure A-1: The Vapor-Compression Refrigeration System**

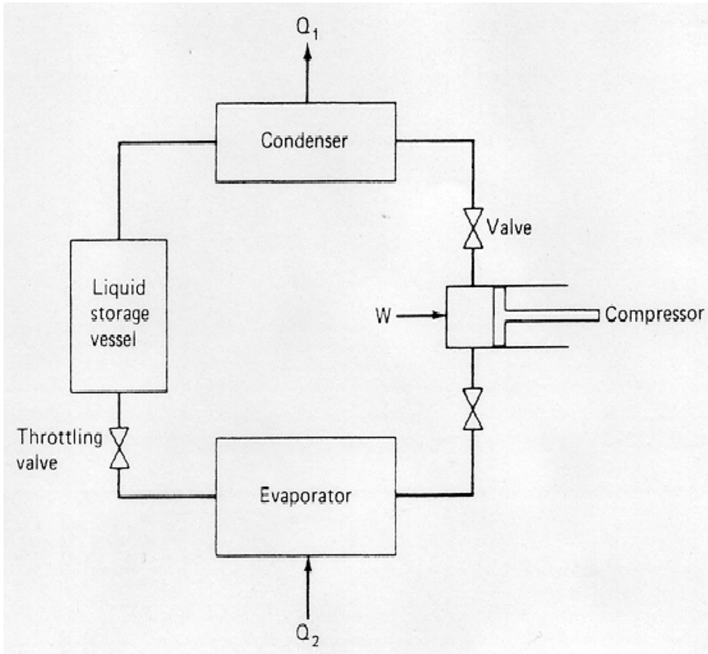



**Table A-1: Refrigerant Criteria**

| | |
|---|---|
| **Chemical** | |
| • | Stable and inert |
| **Health, Safety & Environmental** | |
| • | Non-toxic |
| • | Nonflammable |
| • | Does not degrade the atmosphere |
| **Thermal (Thermodynamic & Transport)** | |
| • | Critical point and boiling point temperatures appropriate for the application |
| • | Low vapor heat capacity |
| • | Low viscosity |
| • | High thermal conductivity |
| **Miscellaneous** | |
| • | Satisfactory oil solubility |
| • | High dielectric strength of vapor |
| • | Low freezing point |
| • | Reasonable containment materials |
| • | Easy leak detection |
| • | Low cost |

Source: "Quest for Alternatives," *ASHRAE Journal*, Dec. 1987

## A.2 CHLOROFLUOROCARBONS (CFCS)

During most of the history of mechanical refrigeration, chlorofluorocarbons (CFCs) have been the most widely used refrigerants. The term chlorofluorocarbons refers to a family of chemicals whose molecular structures are composed of chlorine (Cl), fluorine (F), and carbon (C) atoms. Their popularity has been due in no small part to their desirable thermal properties as well as their molecular stability, among other things.

Chlorofluorocarbons have a nomenclature that describes the molecular structure of the CFC. In order to determine the structure of CFC-11, for instance, one takes the number (11) and adds 90 to it. The result is 101. The first digit of the sum indicates the number of carbon atoms in the molecule, the second the number of hydrogen atoms, and the third the number of fluorine atoms. Any further spaces left in the molecule are filled with chlorine atoms. According to this convention, CFC-11 contains 1 carbon atom, 0 hydrogen atoms, and 1 fluorine atom. Since the carbon atom requires 4 bonds to form a molecule and only one other atom is called for directly by the nomenclature, the remaining three atoms must be filled by chlorine. Hence the molecular formula of CFC-11 is $CCl_3F$. In this fashion it can be seen that the molecular formula for CFC-12 (12+90=102) is $CCl_2F_2$, and that for CFC-113 (113+90=203) is $C_2Cl_3F_3$. In some cases, a letter ("a," for example) is appended to the end of the refrigerant code. This represents a separate isomer of the refrigerant, that is, a form of the molecule with the same proportions of atoms in the molecule, but with a different arrangement of those atoms The letter "R" can be used interchangeably with "CFC" in the nomenclature ("R" stands for "refrigerant").

Of the various chlorofluorocarbons available, the three listed above (CFC-11, CFC-12, and CFC-113) have been the ones used most extensively, due to their desirable physical properties. CFC-11 and CFC-12 are used in refrigeration and foam insulation (CFC-12 is used by virtually all household and mobile air-conditioning systems). CFC-113 is a solvent, used as a cleaning agent for electronics and a degreaser for metals. Table A-2 lists the various uses of CFCs; note that refrigerants account for only a quarter of all CFC applications.

**Table A-2: CFC Applications**

| Use | % |
|---|---|
| Solvents | 26.0 |
| Refrigeration, air conditioning | 25.0 |
| Rigid foams | 19.0 |
| Fire extinguishing | 12.0 |
| Flexible foams | 5.0 |
| Other | 13.0 |

Source: Power, March 1990, p.28.

## A.3 OZONE

The link between chlorofluorocarbons and ozone depletion has been debated over the past twenty years. Much of the impetus for international environmental treaties, such as the Montreal Protocol and legislation such as the Clean Air Act, has come from studies that assert that CFCs, when released into the atmosphere, react with the Earth's ozone layer and eventually destroy it.

The chemistry advanced by these studies suggests that once a CFC molecule drifts high enough into the upper atmosphere, it is broken apart by ultraviolet light. This releases a chlorine atom (Cl), which reacts with an ozone molecule ($O_3$). The reaction produces a chlorine monoxide (ClO) molecule and an ordinary ($O_2$) molecule, neither of which absorb ultraviolet radiation. The chlorine monoxide molecule is then broken up by a free oxygen atom, and the original chlorine atom becomes available to react with more ozone.[34]

## A.4 CFC REPLACEMENTS

Research on finding alternatives to CFCs has focused on trying to find refrigerants that will not affect the ozone layer directly (i.e., those that do not contain chlorine), or refrigerants that, when released into the atmosphere, will break down before reaching the ozone layer, or both.

Three types of CFC replacements being used now and being looked at for future use are hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and their mixtures. HCFCs are similar to CFCs, except that they contain one or more hydrogen atoms, which are not present in CFC molecules. This addition of hydrogen makes these refrigerants more reactive in the

34 Cogan, Douglas G., *Stones in a Glass House: CFCs and Ozone Depletion*, p. 29, Investor Responsibility Research Center Inc., Washington, D.C., 1988.

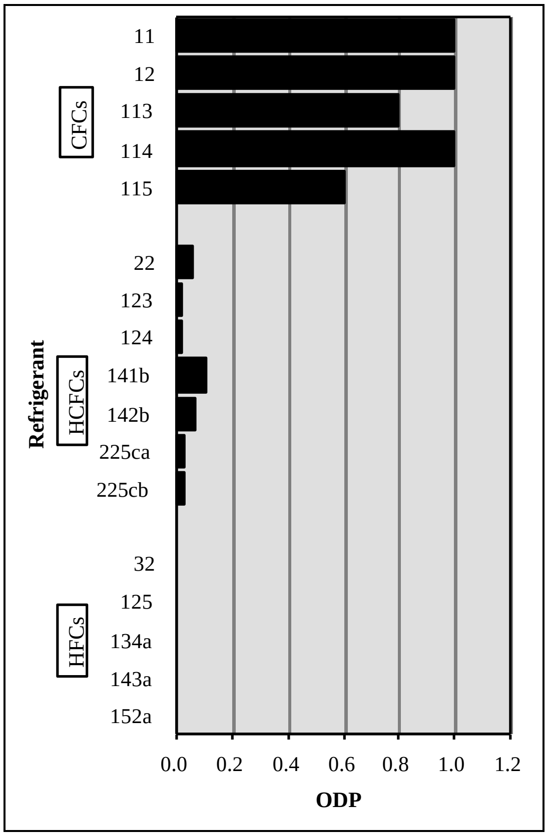
atmosphere, and so less likely to survive intact to higher altitudes. HFCs are similar to HCFCs, except that HFCs do not contain chlorine atoms at all; they are more likely to break up in the lower atmosphere than CFCs, and if they or their degradation products do survive to rise up to the higher atmosphere, they contain no chlorine atoms that can be broken off to react with ozone. Existing phase-out schedules mandate replacing CFCs in the short term, and HCFCs in the longer term. Even though HCFCs are being used as substitutes for CFCs in some cases, this is not a long-term solution. Therefore, there is an eye towards moving directly to HFCs or other long-term solutions as quickly as possible.

The proposed phase-out schedules deal with *production*, not *use*. With recycling, a compound may remain in use long after it is no longer made. However, if it is no longer made, there is a strong incentive to replace it.

The key for those concerned with the environmental effects of refrigerants is a ratio referred to as Ozone Depletion Potential (ODP). A substance's ODP can be found by dividing the amount of ozone depletion brought about by 1 kg of the substance by the amount of ozone depletion brought about by 1 kg of CFC-11. In this fashion, CFC-11 has an ODP of 1.0, and other substances are rated accordingly. ODP levels for various refrigerants are shown in puts the various CFC phase-out strategies into context: moving from high-ODP refrigerants to low-ODP refrigerants in the near term, with the final goal being a move to zero-ODP refrigerants.

Note that HFCs (such as R-134a) have *zero* ozone depletion potential since they contain no chlorine atoms.

**Figure A-2: Ozone Depletion Potentials**




Source: Montreal Protocol