ADVANCED TECHNOLOGY PROGRAM

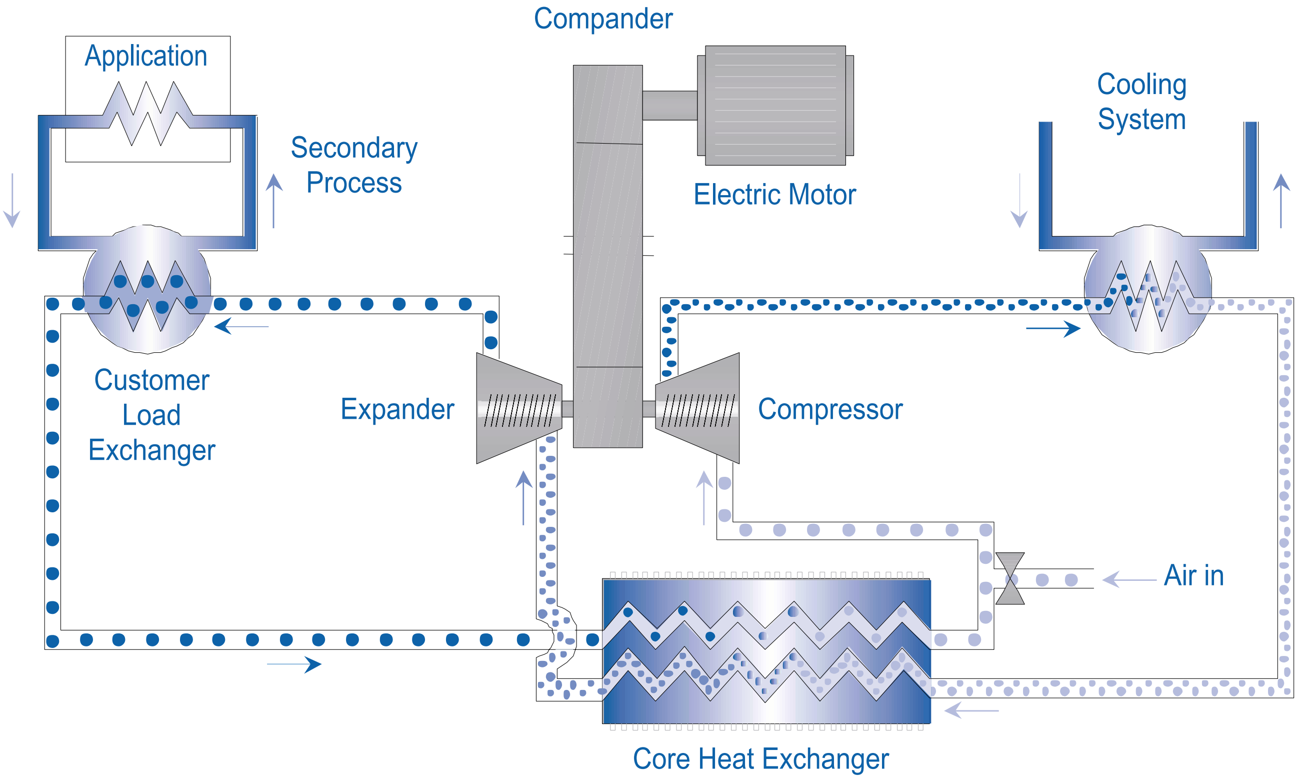
NIST GCR 01-819

Closed-Cycle Air Refrigeration Technology

for Cross-Cutting Applications in Food Processing, Volatile Organic Compound Recovery, and Liquid Natural Gas Industries

Economic Case Study of an ATP-Funded Project

How it works ...



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Economic Case Study of an ATP-Funded Project

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By
Thomas Pelsoci, Ph.D.
Delta Research Co.
Chicago, IL
tpelsoci@deltaresearchco.com

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U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

TECHNOLOGY ADMINISTRATION
Phillip J. Bond, Under Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arden L. Bement, Jr., Director

Abstract

In 1995, the Advanced Technology Program (ATP) co-funded a joint venture project involving two U.S. companies, Air Products and Chemicals, Inc., and Toromont Process Systems, Inc., to design, fabricate, and pilot test closed-cycle air refrigeration (CCAR), a new form of industrial refrigeration technology that uses environmentally benign air as the working fluid. With ATP's $2.1 million investment, matched by $2.2 million corporate investment, this joint venture developed CCAR as a cost-effective industrial refrigeration technology for the ultra-cold (–70°F to –150°F) range. Technology development and successful pilot testing were completed in 1999. Business development and marketing are underway.

Market analyses showed that the U.S. food processing industry will be the most promising end market, where ultra-cold temperatures are useful for:

- Reducing weight loss from evaporation
- Reducing dehydration, for better food taste and quality
- Improving food safety
- Reducing environmental emissions

This case study estimates the following measures of national economic benefit of the ATP investment in the food processing application:

- Net present value: $459–$585 million (2001 dollars)
- Internal rate of return: 83–90 percent
- Benefit-to-cost ratio: 220:1 to 280:1

Additional quantitative and qualitative benefits are reported.

Based on primary research and analysis completed during 2000 and early 2001, the study concludes that:

- These returns have a high probability of being realized.
- It is unlikely that CCAR would have been developed without ATP funding.
- The above benefits can be directly attributed to the ATP investment.

Acknowledgments

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Executive Summary

In its 1995 General Competition, the Advanced Technology Program (ATP) funded a joint venture project, involving Air Products and Chemicals, Inc., and Toromont Process Systems, Inc., to develop closed-cycle air refrigeration (CCAR) technology, using dry air as the working fluid. The project was successfully completed in 1999. Coupled with subsequent corporate product development, it resulted in a cost-effective system for delivering ultra-cold refrigeration in the –70°F to –150°F temperature range to food processing, volatile organic compound, and liquid natural gas applications.

This Executive Summary describes the results of a case study of the CCAR project that includes the history of the ATP-funded CCAR technology development project, a market assessment, and analyses of economic impact. Case study research, analysis and conclusions were completed during 2000 and early 2001.

DEVELOPMENT OF CCAR TECHNOLOGY

Concern over the environmental consequences of the widespread use of ozone-depleting chlorofluorocarbons and hydro-chlorofluorocarbons sparked efforts to develop environmentally benign refrigerants. Alternative refrigerants include ammonia, propane, and mixtures of inert gases (argon, krypton, and xenon). However, ammonia is toxic, propane is explosive, and inert gases are unstable mixtures that are substantially more expensive than chlorofluorocarbons and hydro-chlorofluorocarbons.

Refrigeration systems can also use air as a working fluid. Air is environmentally benign, safe to use, and has an unlimited source. Refrigeration with air as the working fluid is based on the reverse Brayton Cycle. This thermodynamic cycle was discovered in the nineteenth century and has been utilized for air-based refrigeration units in commercial aircraft.

Prior to the ATP-funded CCAR project, air-based systems were configured in an open cycle, where compressed cold air was blown into a cooling chamber and lost for further use. Makeup air had to be continuously dehumidified and compressed to compensate for the loss of cold air, leading to low efficiencies.

To reach improved system efficiencies, Air Products and Chemicals, a major U.S. company active in the refrigeration industry, undertook the technical development of an improved open-cycle air system (ColdBlast™) using complex multi-stage compressors. While this project did not fully meet technical, commercial, and revenue expectations, Air Products engineers concluded that an air-based system, if operated at higher pressure and in closed cycle, could reach improved efficiency levels. They proposed this new approach to management.

No closed cycle system existed before and trying to reach the targeted high efficiency levels would require radical improvements in expander, compressor and heat exchanger technologies. These high risk technology changes were deemed necessary to achieve overall performance levels to make closed cycle systems commercially competitive.

Owing to the less than satisfactory ColdBlast™ experience and the project's high-risk profile, Air Products management decided to de-prioritize further R&D in this area. Encouraged by the ATP funding opportunity, Air Products reversed its decision and convened a multi-disciplinary team to co-develop and cost share this high-risk project with ATP.

In partnership with Toromont Process Systems, Inc., (formerly Lewis Energy Systems), Air Products submitted an ATP application, and ATP selected the joint venture project for an award in its 1995 General Competition. The ATP agreed to cost share $2.1 million of the $4.3 million project. Air Products and Toromont funded the balance.

The project was successfully completed in 1999, culminating in a nine-month pilot test at a Kodak facility. Coupled with subsequent corporate product development, the project resulted in a CCAR system that can cost effectively deliver ultra-cold refrigeration in the –70°F to –150°F temperature range for food processing, volatile organic compound recovery, and liquid natural gas applications.

ASSESSMENT OF MARKET OPPORTUNITIES

An analysis of CCAR market opportunities was completed to provide a basis for estimating the prospective economic impact of this ATP-funded technology development project. The analysis included extensive fact finding in the food processing, refrigeration, marine propulsion, petrochemical, and gas utility industries and a review of available market studies and secondary sources.

CCAR is a niche technology for providing –70°F to –150°F ultra-cold temperatures cost effectively and without harmful environmental emissions to the food processing, volatile organic compound recovery, and liquid natural gas industries.

Conventional mechanical refrigeration systems operate effectively down to –70°F but cannot reach ultra-cold temperatures below –70°F. Liquid nitrogen and carbon dioxide cryogenic refrigeration systems can provide ultra-cold temperatures, but at four times the cost of mechanical refrigeration. CCAR technology is a cost-effective alternative for the –70°F to –150°F niche market, where it is able to deliver ultra-cold refrigeration at half the cost of cryogens.

Market analyses showed that the U.S. food processing industry will be the most promising end market for the CCAR technology, where ultra-cold temperatures are particularly useful for the rapid chilling of precooked, further-processed food products. Through rapid chilling,

- Weight loss from evaporation is reduced. Food items are sold by weight, and avoided weight loss is a direct economic benefit of ultra-cold temperatures.

- Dehydration is reduced, leading to better tasting, higher quality products.

- Food safety is improved. Ultra-cold temperatures facilitate cooked food items cooling down more rapidly through the 141°F to 40°F "danger zone," limiting opportunities for harmful bacteria formation.

Given the advantages of using environmentally benign air to replace harmful refrigerants, ATP-funded CCAR technology is also expected to become an attractive refrigeration alternative for applications beyond food processing, for example, for

- Condensing and capturing harmful volatile organic compound vapor emissions in the chemical, metals, and automotive industries

- Facilitating the replacement of highly polluting marine diesel fuels with clean burning natural gas in the form of liquid natural gas

- Low temperature reactions and storage applications in the petrochemical and pharmaceutical industries

The CCAR technology is currently being marketed and is generating considerable market interest. For example,

- Air Products recently signed a memorandum of understanding with a major food processor for the first commercial installation of a CCAR system.

- Negotiations are underway with other food processors, with a major energy company considering CCAR for hydrocarbon condensing, and with a petrochemical company considering CCAR for ethylene storage.

ECONOMIC IMPACT

The case study focused on identifying *broad-based economic benefits* to the U.S. economy from the ATP-funded CCAR technology. The study examined the effects of improved food safety, higher food processing yields and production rates, improved quality of processed foods, reduced harmful environmental emissions, additional U.S. exports, and cross-industry knowledge diffusion about ATP-funded innovations. Benefits were estimated for a conservative Base Case Scenario and alternative Optimal Scenario.

The case study also identified *direct economic benefits* to ATP's corporate joint venture partners, including incremental revenues derived from commercializing the technology and enhanced organizational capabilities stemming from their ATP experience. ATP's corporate partners control deployment of the CCAR technology through their intellectual property rights. Direct economic benefits to these companies will provide the motivation to sustain an effective marketing program which will be a prerequisite for diffusing the technology and turning the ATP's investment into broad-based benefits for the U.S. economy.

To develop projections of CCAR's broad-based economic impact, the case study estimated the number of units to be deployed over the 2002–2016 period. Under a conservative Base Case Scenario, the study posited that Air Products would deploy 17 CCAR units at U.S. food processing plants, including 10 units to replace cryogenic refrigeration and 7 units to boost or replace mechanical refrigeration. Under the Optimal Scenario, the study posited the deployment of approximately 20 percent higher number of units.

The case study estimated prospective cash flow benefits from CCAR installations, measured in 2001 dollars. The estimated cash flows were used to project several measures of the public return on ATP's investment: net present value (NPV), internal rate of return (IRR), and benefit-to-cost ratio.

For the Base Case Scenario, the benefit-to-cost ratio was projected to be 220:1; that is, with all cash flows normalized to 2001 dollars, a public return of $220 was projected for every dollar of ATP investment. The Base Case IRR, another measure of public return from ATP's investment, was 83 percent. The Base Case NPV from ATP's investment was projected at $459 million. Of this amount, CCAR-induced food quality improvements represented 66 percent, yield improvements 25 percent, and faster production rates only 1 percent. CCAR-induced cost savings from replacing liquid nitrogen and carbon dioxide cryogens represented 7 percent of NPV.

The **net present value (NPV)** was calculated by subtracting the present value of ATP investments from the present value of incremental cash flows, attributable to improved food quality, processing yield, etc. All cash flows were normalized to 2001 dollars and discounted at the 7 percent OMB-designated rate. This measure describes the net total benefit to the nation, in 2001 dollars.

The **internal rate of return (IRR)** was calculated by iterative solution for a rate at which the discounted value of ATP's investment would equal the discounted value of incremental cash flows. This measure describes the rate of return to the nation on ATP's investment .

The **benefit-to-cost ratio** of ATP's investment was computed by dividing the present value of cash flow benefits by the present value of ATP's investment. This measure shows the benefit to the nation for every dollar of ATP investment.

The Optimal Scenario resulted in a benefit-to-cost ratio of 280:1, an IRR of 90 percent, and an NPV of $585 million.

An additional dimension of the public return from ATP's investment is the potential for the CCAR technology to generate additional U.S. exports. For the Base Case Scenario, exports were estimated to increase by an average of $4.8 million each year over the period 2004–2016. For the Optimal Scenario, exports were estimated to increase an average of $6 million each year.

In addition to the substantial public benefits to the U.S. economy, the case study estimated private benefits to Air Products and Toromont from commercializing CCAR technology. The present value of projected revenues from CCAR installations in the food service, volatile organic compound, and liquid natural gas industries was projected to be $65 million. Although available information was insufficient for estimating the resulting profit contribution, $65 million projected revenues appears adequate to support Air Products' continued commitment to sell, support, and service the CCAR refrigeration technology.

In addition to the above quantifiable economic benefits, CCAR technology is associated with the following qualitative benefits:

1. *Improved food safety in food processing industry:* Even when fully cooked, food items can grow bacteria in the 40°F to 141°F temperature range, the so-called "danger zone." CCAR is an innovative refrigeration technology that accelerates the rate of cooling for cooked and further-processed foods, facilitating quick passage through the "danger zone" and reducing public health risks from food borne bacteria.

2. *Improved food safety and reduced operating costs in the food service (restaurant and fast food) industries*: The food service industry is subject to Hazard Analysis and Critical Control Points (HACCP) safety regulations, requiring time-consuming monitoring of foods in the 40°F to 141°F temperature range. By using precooked, further-processed foods, food service establishments avoid bringing temperatures up to cooking levels. This has the effect of reducing operating costs by limiting time-consuming labor requirements mandated in HACCP regulations.

3. *Reduced diesel emissions from hauling liquid nitrogen and carbon dioxide*: CCAR is a distributed refrigeration technology, installed onsite, at the point of use. Use of CCAR instead of hauling cryogens from regional air separation and carbon dioxide plants will avoid diesel emissions from 12,000 to 14,000 roundtrips per year of truck shipments.

4. *Reduced diesel emissions from ocean-going vessels*: Air emissions from cargo ships and ocean-going ferries powered by diesel engines are among the most polluting combustion sources per ton of fuel consumed. Use of CCAR refrigeration for dockside liquid natural gas facilities and replacement of marine diesel fuel with liquid natural gas are expected to provide up to 98 percent reduction of carbon monoxide emissions, 55 percent reduction in nitrogen oxide emissions, and 95 percent reduction in particulates.

5. *Cross-industry knowledge diffusion*: CCAR technology was chosen as a finalist for the Kirkpatrick Award in the November 1999 issue of *Chemical Engineering Magazine* in recognition of its "step-out" performance levels. It is expected that cross-industry knowledge dissemination about the performance improvements associated with the design and fabrication of CCAR system components will lead to expanded utilization of low leakage seals, high pressure heat exchangers, and innovative investment casting technologies in other industries.

6. *Enhanced organizational capacity*: On the basis of the ATP-funded CCAR experience, both Air Products and Toromont reported enhanced organizational capabilities. Air Products Cryomachinery Laboratory adapted the use of advanced computational fluid dynamics methodologies for routine engineering design. Encouraged by its successful joint venture experience with Air Products, Toromont entered into a new strategic alliance with Allison Chalmers.

CONCLUSIONS

The case study concludes that the new CCAR technology has made significant progress toward meeting the necessary conditions for commercialization and market acceptance. These conditions are:

- Successful completion of technical development and demonstration phases
- Market studies indicating substantial demand in the food processing industry
- Informal market intelligence indicating good potential in the volatile organic compound recovery, liquid natural gas, pharmaceutical, and petrochemical industries
- Technological advantages that can be translated into business advantages
- Continued active marketing of CCAR systems by Air Products

Based on these elements of progress, it is anticipated that public returns from ATP's CCAR investment, broad-based economic benefits to the food processing industry and consumers, and substantial environmental benefits from avoided refrigerant and transport emissions have a high probability of being realized.

Furthermore, it is unlikely that CCAR technology would have been developed without ATP funding. Following a less than fully satisfactory development experience with the ColdBlast^{TM} open-cycle air refrigeration system, Air Products made the decision to de-prioritize the development of the high-risk closed-cycle CCAR technology. Hence, the above quantitative and qualitative benefits to the U.S. economy can be directly attributed to ATP's CCAR investment. These benefits are summarized in Table 1.

Table 1. Benefits from ATP's CCAR Investment

Broad-Based, Cross-Industry Benefits
Food processing industry
Net present value of ATP's investment: $459–$585 million
Internal rate of return on ATP's investment: 83–90 percent
Benefit-to-cost ratio on ATP's investment: 220:1 to 280:1
Additional U.S. exports of $5–$6 million each year
Enabling technology for improved food safety
Avoided annual diesel emissions from 12,000 to 14,000 truck shipments of cryogens
Food service industry
Enabling technology to reduce food preparation labor costs
Liquid natural gas industry
Enabling technology to reduce marine diesel emissions via liquid natural gas utilization
Cross-Industry Knowledge Diffusion
Finalist for the Kirkpatrick Award in *Chemical Engineering Magazine*
Expanded usage of innovative technologies, associated with CCAR
Benefits to Industry Partners
Enhanced organizational capabilities at Air Products and at Toromont

Table of Contents

Abstract . . . iii

Acknowledgments . . . iv

Executive Summary . . . v
Development of CCAR Technology ...v
Assessment of Market Opportunities ...vi
Economic Impact ...vii
Conclusions ...x

1 Introduction . . . 1
Case Study Objectives and Scope ...1

2 Development of CCAR Technology . . . 3
How CCAR Works ...3
ATP Project History ...4
Major Innovations ...5

3 Overview of Target Industries . . . 9
Food Processing Industry ...10
Secondary Markets for CCAR ...20

4 Economic Impact . . . 27
Assumptions ...27
Quantitative Benefits to the U.S. Economy ...30
Qualitative Benefits ...33

5 Conclusions . . . 39

6 Glossary . . . 41

7 Interviews . . . 45

8 References . . . 47

9 Related Reading . . . 49

Appendix A: CCAR Technical Characterization....51
Refrigeration Technologies 51
Kodak Demonstration 54
CCAR Configuration in Food Processing 55
Innovations From CCAR Development 58

Appendix B: Base Case Calculations....63

Appendix C: Optimal Scenario Calculations....69

About the Advanced Technology Program ....Inside Back Cover

About the Author ....Inside Back Cover

List of Figures

Figure 1. CCAR Refrigeration System 3
Figure 2. U.S. Food Industry Value Chain 10
Figure 3. Market Drivers for the Further-processed food Industry 12
Figure 4. The Food Freezing Process 15
Figure 5. Manufacturing Further Processed Meat Products 16
Figure 6. Survey of Food Companies' Interest in CCAR Refrigeration 18
Figure 7. Geographic Distribution of 57 Liquid Natural Gas Peak Shavers in the United States 23
Figure A1. Conventional Mechanical Refrigeration System 52
Figure A2. CCAR System 53
Figure A3. Food Processing Plant CCAR Configuration 55
Figure A4. Food Processing Plant with Mechanical Refrigeration 56
Figure A5. Food Processing Plant with Cryogenic Refrigeration 57

List of Tables

Table 1. Benefits from ATP's CCAR Investment xi
Table 2. CCAR Compared With Alternative Technologies 9
Table 3. U.S. Processed Food Sales 11
Table 4. Secondary Market Opportunities for CCAR 21
Table 5. Base Case Projections for Number of U.S. Food Industry CCAR Installations 27
Table 6. Optimal Case Projections for Number of U.S. Food Industry CCAR Installations
Table 7. ATP Investment Normalized to 2001 Dollars 30
Table 8. Base Case Cash Flows from Improved Quality, Yield, and Production Rates and from Reduced Refrigeration Costs 31
Table 9. Base Case Net Present Value, Internal Rate of Return, and Benefit-to-Cost Ratio . . 32
Table 10. Optimal Scenario Net Present Value, Internal Rate of Return and Benefit-to-Cost Ratio 32
Table 11. Air Products Revenue Streams from Base Case 34
Table 12. Emission Characteristics of Natural Gas–Fueled Transportation Vehicles Versus Diesel-Fueled Vehicles 36

Table A1. Comparison of Freezing Systems 58
Table B1. Projected CCAR Units, Base Case 63
Table B2. Cash Flow From Improved Quality, Base Case 64
Table B3. Cash Flow From Improved Food Processing Yield, Base Case 65
Table B4. Cash Flow From Food Processing Throughput, Base Case 66
Table B5. Cash Flow From Replacing Cryogenic Systems, Base Case 67
Table B6. Combined Cash Flow, Base Case 68
Table C1. Projected CCAR Units, Optimal Scenario 69
Table C2. Cash Flow From Improved Quality, Optimal Scenario 70
Table C3. Cash Flow From Improved Food Processing Yield, Optimal Scenario 71
Table C4. Cash Flow From Food Processing Throughput, Optimal Scenario 72
Table C5. Cash Flow From Replacing Cryogenic Systems, Optimal Scenario 73
Table C6. Combined Cash Flow, Optimal Scenario 74

1 Introduction

The Advanced Technology Program (ATP), National Institute of Standards, fosters partnerships among government, industry, and academia by co-funding innovative, high risk research to develop enabling technologies that promise broad economic benefits for the nation.

In 1995, ATP funded development of an innovative refrigeration technology for providing ultra-cold refrigeration in the –70°F to –150°F range with potential applications in the food processing, volatile organic compound recovery, and liquid natural gas industries. The project encompassed technology development, system integration, fabrication, and pilot testing of a closed-cycle air refrigeration (CCAR) system that would utilize environmentally benign dry air as the working fluid.

The ATP conducts economic analyses to assess the short- and long-run benefits of ATP-funded projects to the nation. It evaluates impacts on project participants, their customers, final consumers, and other recipients of the technologies developed with ATP assistance. This case study of ATP's CCAR project is part of ATP's ongoing evaluation effort.

CASE STUDY OBJECTIVES AND SCOPE

The objectives of this case study are to summarize key technical features of the enabling CCAR technology developed with ATP funding, to describe associated market opportunities, and to identify, characterize, and quantify the economic impact of the project.

The case study is aimed at evaluating

- Broad-based economic benefits, across multiple U.S. industries
- Public returns from ATP's investment
- Knowledge dissemination about useful technical innovations
- Improved organizational capabilities for ATP's industry partners
- Private returns for ATP's industry partners

Analysis focused on the estimation of quantifiable public returns for the U.S. economy, as measured against ATP's investment over the 1996–1998 period. The analysis also identified economic benefits that could not be quantified at this time.

2 Development of CCAR Technology

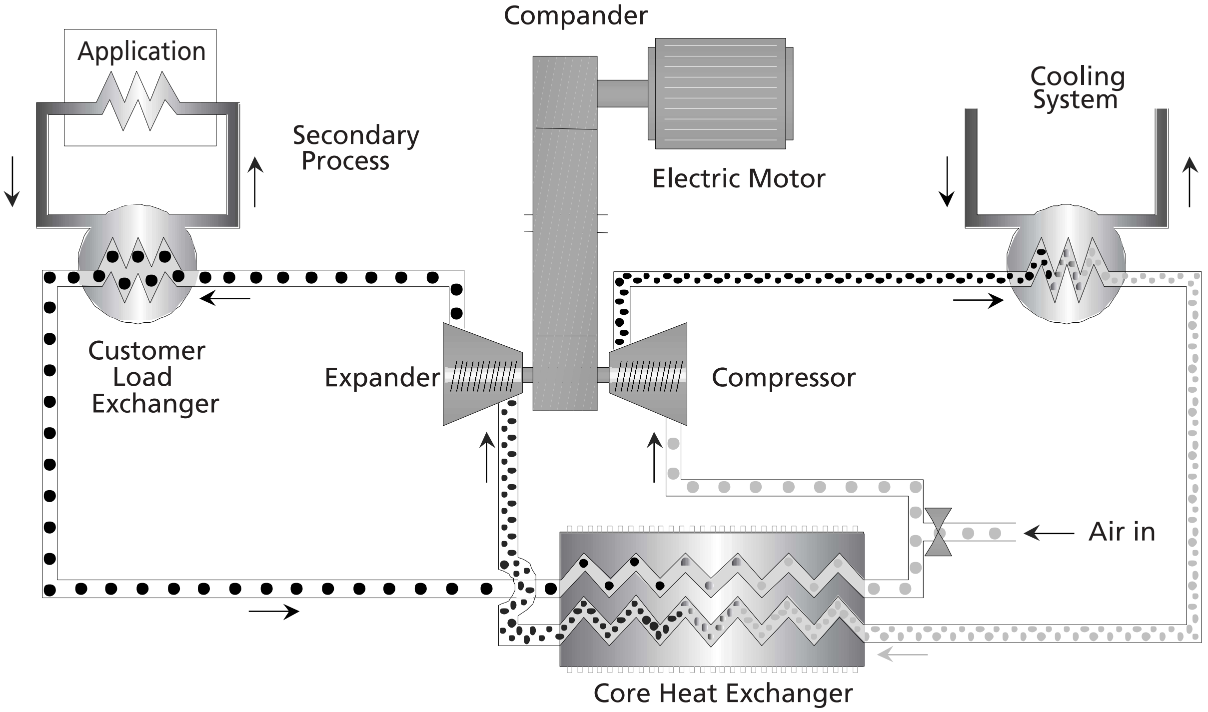
HOW CCAR WORKS

Refrigeration is the withdrawal of heat from items to be refrigerated to achieve lower than ambient temperatures. After heat is withdrawn, it is transferred to a condenser and dissipated to air or water.

Closed-cycle air refrigeration (CCAR) is a new refrigeration technology, combining components from mechanical and cryogenic refrigeration, expanding component capabilities, and integrating components in innovative ways for meeting necessary "step-out" performance conditions. The system uses dry, high-pressure air as the working fluid and is configured as a closed system to avoid the need for continuous moisture removal from makeup air. Moisture freezes, and the resulting ice particles on turbine blades can damage rotating equipment. CCAR avoids this problem through the closed-cycle configuration. Unlike conventional refrigeration systems, high-pressure air is in a gaseous state throughout the cycle, without phase change. Figure 1 indicates key CCAR components and system connections.

Figure 1. CCAR Refrigeration System

How it works ...



A U.S. patent for the basic CCAR technology was issued in 1996 (Miller, Smith, Allam, and Topham, U.S. Patent 5483806, Refrigeration System, January 1996). The Advanced Technology Program (ATP) funded project involved development of technologies for radically improved efficiencies in the expander, compressor, and heat exchanger, as well as advanced system integration, detailed design, fabrication, and a test program (for more details, see Appendix A, "Innovations From CCAR Development.")

ATP PROJECT HISTORY

Concern over the environmental consequences of the widespread use of ozone-depleting chlorofluorocarbons (CFC) and hydro-chlorofluorocarbons (HCFC) sparked efforts to develop environmentally benign alternatives for these common industrial refrigerants. Alternatives include ammonia, propane, and inert gas combinations of argon, krypton, and xenon. However, ammonia is toxic, propane is explosive, and inert gases are unstable mixtures that are substantially more costly than CFC and HCFC.

Air is another alternative working fluid for industrial refrigeration systems. It is environmentally benign, safe to use, and has an unlimited source. Using air for refrigeration is not a new concept. The air refrigeration cycle (the reverse Brayton Cycle) was developed in the nineteenth century and has been used in specialized applications including air conditioning systems for commercial aircraft.

Prior to the ATP-funded CCAR technology, air-based refrigeration systems utilized an open cycle (Verschoor and van der Sluis, TNO Department of Refrigeration & Pump Technology (Interview)) where compressed cold air is blown into a cooling chamber and lost for further use in the cycle. Makeup air is continuously dehumidified and compressed to compensate for the loss of cold air, leading to low system efficiencies and high energy costs.

To reach improved system efficiencies, Air Products and Chemicals, Inc., a major U.S. company active in the food refrigeration industry, undertook the technical development of the open-cycle air system by using complex multi-stage compressors. The open-cycle ColdBlast™ initiative did not fully meet technical, commercial, and revenue expectations. Air Products engineers concluded that an air-based system, if operated at higher pressure and in closed cycle, could reach improved efficiency levels. No such system had existed before, but theoretically, the concept was feasible with the development of new, more efficient components and optimized system operation. They proposed the new approach to management.

Owing to the less than satisfactory ColdBlast™ experience and the project's high-risk profile compared with alternative R&D opportunities, Air Products management decided to de-prioritize further R&D in this area. This decision also reflected a preference for efficiency improvements of existing products as opposed to the development of radically innovative, longer time-to-market technologies.

ATP Joint Venture Project Partners

Air Products and Chemicals, Inc., is a leader and innovator in the fields of industrial gases, cryogenic air separation, food freezing, and chilling technologies. The company is headquartered in Pennsylvania's Lehigh Valley and has annual sales of $5 billion and conducts business in more than 100 countries.

Toromont Process Systems is a subsidiary of Toromont Industries, Inc., with 1999 revenues of $723 million. Toromont provides design and modular fabrication for industrial refrigeration and compression systems and has a 30-year business relationship with Air Products.

Encouraged by the ATP funding opportunity, Air Products reversed its decision and convened a multi-disciplinary team to co-develop and cost share the project with ATP. In partnership with Toromont Process Systems, Inc. (formerly Lewis Energy Systems), Air Products submitted a joint venture proposal to ATP to develop a high pressure, CCAR technology suitable for widespread industrial use.

In its 1995 General Competition, ATP selected the joint venture project for an award. The project encompassed technology development, system integration, fabrication, and demonstration of a CCAR system that would utilize environmentally benign dry air as the working fluid. The core challenge was to greatly improve efficiency of the expander, compressor, and heat exchanger, and optimize system operations. The ATP agreed to cost share $2.1 million of the $4.3 million project, and Air Products and Toromont committed to fund the balance.

Throughout the project, Air Products provided process engineering and technical expertise for pushing system components to step-out performance levels, required by the demanding operating conditions of a high pressure, CCAR system. Toromont provided engineering and technical expertise in the areas of packaged refrigeration, heat transfer, fabrication, and food processing application expertise.

Complementing the skill sets of Air Products and Toromont engineers, specialty contractors were used for compressor shaft seal design (FlowServe), high-pressure heat exchanger design (Chart Heat Exchanger), and innovative casting solutions for the expander turbine (Quick Cast).

MAJOR INNOVATIONS

The project was successfully completed in 1999. During the ATP-funded technology development, design, and testing phase, CCAR efficiency and operating reliability levels were improved and costs brought down relative to the costs of cryogenic refrigeration. The key elements of technical progress for improving efficiency, reliability, and costs included:

- Operating at high pressures (1,200 psig), in combination with –150˚F temperatures and 30,000 rpm compander shaft speeds. In combination, these were step-out conditions, requiring significant technical advances.

- Utilizing a single wheel compressor and expander designs, compared to more expensive cryogenic systems with multi-staged compressors and expanders.

- Utilizing a low compression ratio (compressor output to expander output) of 1.6 to 1 compared to cryogenic machines operating at ratios of 8 to 1.

- Developing ultra low leakage seals, to prevent high pressure air escaping at the compressor shaft at more than two standard cubic feet per minute.

- Developing a high efficiency heat exchanger with no more than 2˚F to 3˚F temperature difference between high pressure air exiting the cooling system and the return air from the load exchanger.

The CCAR test program included bench tests at Air Products' Cryomachinery Laboratory and a nine-month pilot test program at a Kodak facility in Rochester, New York. The demonstration unit was operated for 6,000 hours and reached or exceeded design specifications.

- Unit output was specified at 50 tons of refrigeration. One ton of refrigeration is a measure of refrigeration capacity sufficient to freeze one ton of water. The plant operated at 60 tons, exceeding the design point by 20 percent.

- System reliability was targeted at 95 percent. The plant operated at 98 percent, exceeding expectations by 3 percent.

- Refrigeration temperatures were maintained within a close (+/–2°F) band around the –100°F design point.

- At –70°F, the demonstration unit achieved a 0.75 COP (coefficient of performance) level, consistent with COP levels of conventional mechanical refrigeration units. The COP measures the relative efficiencies of different refrigeration systems. At –100°F, a temperature level that conventional mechanical refrigeration units cannot reach, the unit operated at a targeted 0.66 COP design point.

- With 40 percent turndown (load reduction), CCAR unit efficiency decreased by only 3 percent. Comparable 40 percent turndown of a conventional mechanical refrigeration unit resulted in 37 percent efficiency reduction.

- Operating at less than 85 decibels, CCAR satisfied Occupational Safety and Health Administration equipment noise-level regulations.

An overall assessment by the Kodak project engineers was that "CCAR met or exceeded all acceptance criteria" and successfully demonstrated its technical feasibility" (W. Klumpp, Kodak CCAR Demonstration Project Manager, Correspondence to E. Kiczek of Air Products and Chemicals, June 30, 1998).

Some of the innovations developed to address the CCAR step-out conditions have potential usefulness to other industrial applications and represent opportunities for cross-industry technology diffusion. For example:

1. *Improved shaft seals*. Successful performance of dry gas seals under the severe CCAR operating conditions (the combination of 1200 psig pressure, –150°F temperature, and 30,000 rpm shaft speed parameters) is expected to promote greater industry acceptance of DGS technology (Klossek, FlowServe (Interview)).

2. *High pressure core heat exchanger.* The new high-efficiency aluminum plate core heat exchanger fabricated by Chart Heat Exchangers (CHE) for CCAR has potential applications in the petrochemical, air separation, and natural gas industries. The new shop and fabrication processes employed by CHE for CCAR are expected to result in an increase in market share for this U.S. company.

3. *Improved casting technology.* To fabricate mold prototypes for the CCAR expander wheel, Air Products Cryomachinery Laboratory used three-dimensional rapid prototyping technology with Quick Cast honeycombed advanced materials. This innovative approach significantly reduced the time and cost requirements of building prototypes and facilitated the evolutionary development process for optimizing CCAR performance (Tomasic, Air Products (Interview)).

Appendix A provides a more in-depth description of the CCAR technology and technical accomplishments of the ATP project.

3 Overview of Target Industries

An extensive analysis of the various segments of the food processing industry was undertaken to assess the market opportunities for the closed-cycle air refrigeration (CCAR) technology. Opportunities for use outside food processing were also explored. Fact finding included interviews of individuals in the food processing, refrigeration, marine propulsion, petrochemical, and gas utility industries as well as a review of available market studies and secondary resources. The further-processed food segment showed the greatest promise of growth and benefit from CCAR's niche capabilities.

CCAR is a niche technology for providing –70°F to –150°F ultra-cold temperatures cost effectively and without harmful environmental emissions to the food processing, volatile organic compound recovery, and liquid natural gas industries. Table 2 compares CCAR technology with mechanical and cryogenic refrigeration for food processing.

Table 2. CCAR Compared With Alternative Technologies

Mechanical refrigeration	*CCAR*	*Cryogenic refrigeration*
Warmer than –70°F	–70°F to –150°F	Colder than –70°F
90 percent of refrigeration systems for small, intermediate, and large food processing plants	17 CCAR units to be deployed at large food processing plants	2,200 mini systems at small food processing plants
Onsite refrigeration system	Onsite refrigeration system	Cryogens hauled in from regional liquid nitrogen and carbon dioxide plants

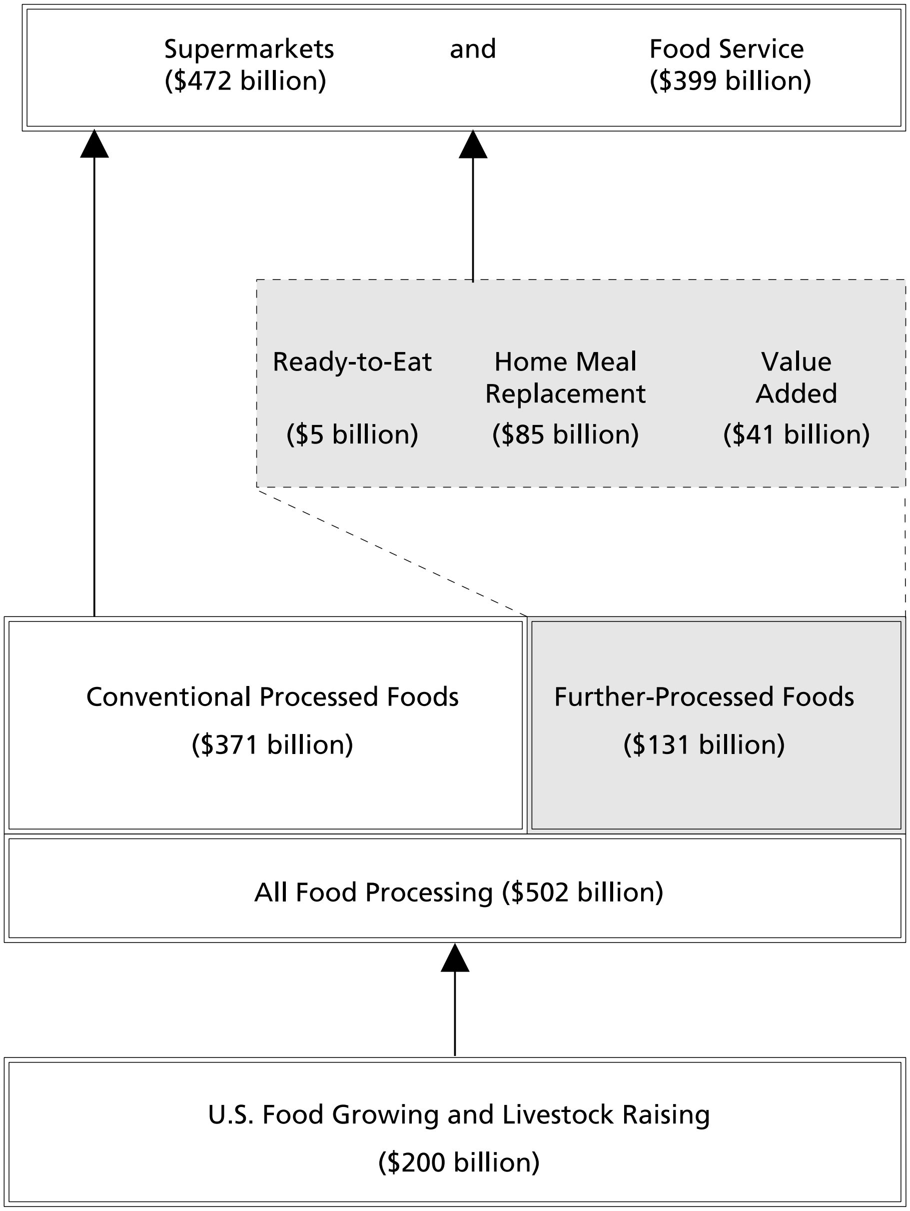
Conventional mechanical refrigeration systems operate effectively down to –70°F but cannot reach ultra-cold temperatures below –70°F. Liquid nitrogen and carbon dioxide cryogenic refrigeration systems can provide ultra-cold temperatures, but at four times the cost of mechanical refrigeration. CCAR is a cost-effective alternative for the –70°F to –150°F niche, delivering ultra-cold refrigeration at half the cost of cryogens.

FOOD PROCESSING INDUSTRY

Food growing and processing represents one of the largest industries in the U.S. economy, with more than $700 billion in annual sales. At the beginning of the supply chain, the agriculture and livestock sectors generate annual sales of $200 billion. Next in the chain are food processors, which convert crops, livestock, and dairy products into processed foods and generate annual sales of $502 billion (Morris, 2000).

As indicated in Figure 2, supermarkets and food service establishments complete the value chain.

Figure 2. **U.S. Food Industry Value Chain**



- Fresh and processed foods are sold at retail through groceries and supermarkets.
- This segment represents annual (1999) sales of $472 billion (*Progressive Grocer*, 1999).
- Food items are sold wholesale to the food service industry (restaurants, fast food, and institutional markets). The food service industry generates annual (2000) sales of $399 billion (National Restaurant Association, 2001).

Food Processing Industry Trends

Sales revenues from processed foods have grown at an average annual rate of about 2 percent (Table 3). While this average rate is expected to continue, certain segments of the processed foods industry are projected to grow at significantly higher rates. Major industry segments include:

- Room temperature items, such as cereals, canned foods, and bakery products.
- Refrigerated or frozen items, including meats, poultry, and seafood. Processing steps are limited to slaughter, washing, chilling to facilitate cutting up, weighing, grading, product forming in tumblers and presses, freezing, and packaging.
- Further-processed foods, including meats and poultry items that are marinated, seasoned, cooked, combined with vegetables and other items, and frozen.

Table 3. **U.S. Processed Food Sales ($billions, current dollars)**

1990	$392
1991	$398
1992	$407
1993	$422
1994	$431
1995	$447
1996	$461
1997	$471
1998	$491
1999	$502

Source: Morris (2000).

Further-Processed Foods

The $131 billion further-processed food segment is projected to experience rapid growth. Since this segment also specifically benefits from CCAR's ultra-cold niche capabilities, it is an attractive end market for the Advanced Technology Program (ATP) funded CCAR technology.

- A 1998 survey of the U.S. broiler industry indicated that "further-processed food production has grown over 6 percent per annum against 2 percent growth for the broiler industry" (*Broiler Industry*, 1998).
- The "further-processed foods market is the fastest growing segment of the foods and beverage marketplace. It is expected to achieve an annual growth rate of 13 percent between 2000 and 2005." (*Refrigerated & Frozen Food Processor*, 2000)

As indicated in Figure 2, the further-processed food industry is segmented into several components, each with different economic characteristics.

- Value-added meats and poultry are sized, seasoned, marinated, precooked, and sold to the food service industry and require some additional preparation before serving. U.S. sales in 1999 were $41 billion.

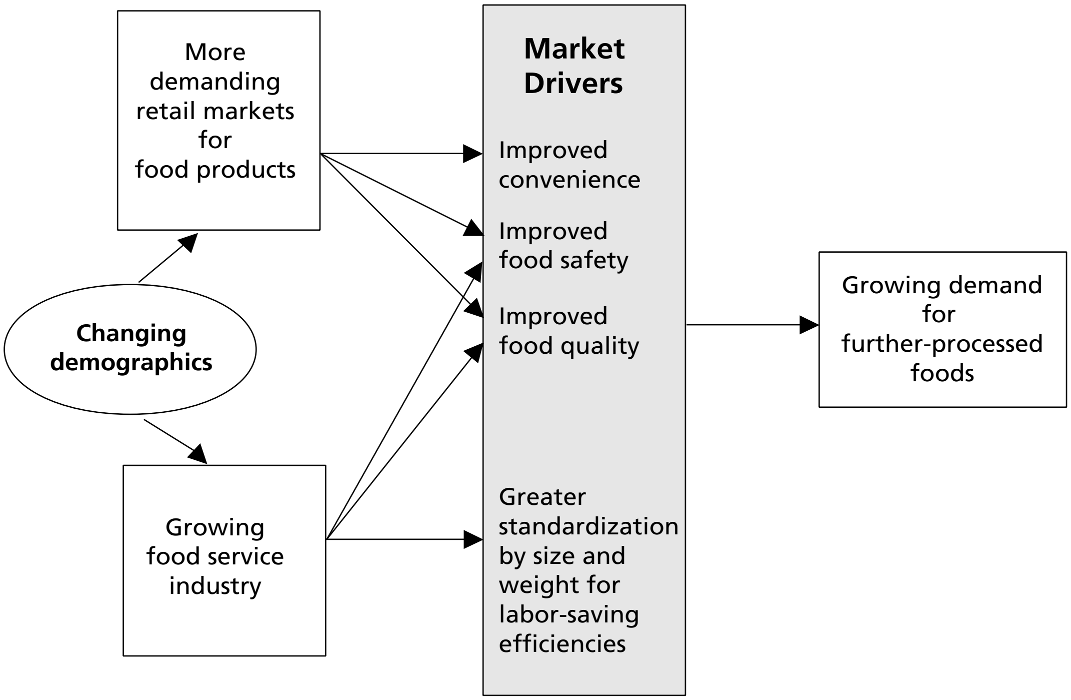
- When sold to retail customers, value-added meals are tagged as “home meal replacement items.” U.S. sales in 1999 were $85 billion. This market segment is expected to grow to $109 billion by 2002 (American Frozen Food Institute, 2000).

- Ready-to-eat meals, sold to retail customers as complete meals, are ready for microwaving without additional preparation. U.S. sales in 1999 were $5.3 billion.

Twenty-five percent of restaurant owners expect to increase utilization of further-processed foods over the next five years (National Restaurant Association, 2001).

Figure 3 indicates the key market drivers of the further-processed food industry: convenience, food safety, food quality, and food product standardization.

Figure 3. Market Drivers for the Further-processed food Industry



CHANGING DEMOGRAPHICS

The underlying factor behind the rapidly growing demand for further-processed foods is demographic change (Figure 3). "As the number of employed persons in the U.S. continues to increase, the amount of time left to prepare meals at home continues to fall. Nearly 4 out of 10 adults (39 percent) reported that they are cooking fewer meals at home than two years ago. Nearly 3 out of 10 adults reported that purchasing takeout food items is essential to the way they live. This trend is more pronounced among younger adults with 47 percent between the ages of 18 and 24 reporting extensive use of takeout foods" (National Restaurant Industry Association, 2001).

"Spending less than 20 minutes per day preparing foods at home, today's consumers demand convenience, quality and value." *Refrigerated & Frozen Food Processor* (2000)

Time-pressed patrons have fueled the growth of further processed (value-added and ready-to-eat) retail foods and, given their increasing affluence, have supported 5 percent annual growth rates in the restaurant, fast food, and take-out food service sectors. In 2001, the restaurant industry will post its tenth consecutive year of real sales growth (National Restaurant Industry Association, 2001).

The underlying demographic factors associated with the growth of further-processed foods can be resolved into four market drivers.

Market Driver 1: Improved Convenience. "As the foodservice industry enters the new millennium, consumer macro trends indicate increased demand for convenient, value added prepared food products at a fair price" (American Frozen Food Institute, 2000). In 1998, the industry responded with a record number (28 percent increase) of new product introductions; that is, new ready-to-eat dinners and entrees, component meals, holiday meals, pizzas, appetizers, and meat, poultry, and seafood products (*Refrigerated & Frozen Food Processor*, 2000).

Market Driver 2: Food Safety. Food safety, along with drinking water safety, ranks high as a key public sector concern. Bacteria, such as E.coli, salmonella, and listeria, remain the top food safety issues.

Hazard Analysis and Critical Control Points (HACCP) is a U.S. government regulatory measure to prevent food safety problems.

HACCP plans became mandatory for federally inspected U.S. meat and poultry plants, as of January 2000.
American Meat Institute, 2000.

The Internet is emerging as a source of information about food safety. In 1999, 23 percent of consumers ranked the Internet as their main source of food safety information (Morris, 2000).

Food safety concerns have resulted in increased demand for fully cooked products, such as fully cooked sausages and meat dishes (*Refrigerated Foods*, 2000). However, any food, even if fully cooked, can grow bacteria in the 40°F to 141°F temperature range, the so-called "danger zone." The U.S. Food and Drug Administration and the U.S. Department of Agriculture Food Safety and Inspection Service advise consumers to ensure that even precooked and ready-to-eat meals are refrigerated to below 40°F (American Meat Institute, 2000). CCAR is an innovative refrigeration technology that can accelerate the rate of cooling of hot, cooked, further-processed foods. That is, CCAR can facilitate passing through the "danger zone" quickly, thereby minimizing food safety concerns.

Market Driver 3: Food Quality. In the retail and food service markets, customer satisfaction with freshness, taste, and appearance (that is, food quality) have been steadily improving. Both retail and food service companies are in highly competitive industries and understand that quality wins and retains customers (National Restaurant Industry Association, 2001). As Figure 5 indicates, freezing is an important step in producing high quality, further-processed foods.

Market Driver 4: Standards and Labor Savings. In the food service industry, product quality and consistency are paramount. Obtaining the necessary quality and consistency levels can be labor intensive. When food service establishments purchase precooked items that are standardized per weight, size, and moisture content, several steps in the labor-intensive meal preparation process can be avoided. Using precooked foods also eliminates the need to bring food temperatures up to cooking levels and makes it possible to avoid time consuming compliance with Hazard Analysis and Critical Control Points regulations.

SUMMARY

The rapidly growing U.S. further-processed food segment is responding to the key market drivers through the introduction of a rich variety of new products.

Examples of Further-Processed Food Products

Cambridge Foods: Microwaveable chicken, beef, pork items with sauces, pasta, rice, and vegetable components.

Elmira Poultry: Portion-controlled products such as breaded chicken fingers, nuggets, and burgers, fully cooked and flavored wings, and fully cooked quarter chickens.

J. D. Sweid & Co.: Fully cooked chickens and ribs, wings, teriyaki chicken breast, beef patties, roasts, and chili.

Premier Choice Gourmet Entrees: Cordon bleu, chicken meatballs, turkey meatballs.

The ATP-funded CCAR technology is poised to become an effective enabling and cost-effective technology for meeting the market demands of convenience, food safety, food quality, and standardization. Figure 4 provides a summary of the food freezing process.

Figure 4. The Food Freezing Process

Food freezing is a complex chain of biochemical and physical processes. Water is a major constituent of foods, comprising from 55 to 95 percent of total mass and, in a pure form, freezes at 32°F. The water content of food is not in a pure form but in the form of a solution, carrying dissolved fats and other organic solutes, which act as a type of antifreeze, and lowering the freezing temperature of the solution. As some of the water freezes, the solution becomes progressively more concentrated, leading to the gradual reduction in the freezing point of the remaining solution (Barbosa-Canovas and Vega-Mercado, 1996).

As the water content of food freezes, ice crystals are formed. The larger size crystals tend to break down food texture, rupture cell walls, and release degenerative enzymes, leading to loss of quality (Erickson and Hung, 1997).

An effective means of slowing down the formation of large ice crystals (and thereby delaying the loss of quality) is to plunge the product through the freezing temperature range rapidly. As test results by Air Products indicate, colder freezing is linked to faster freezing and improved quality.

Freezer Temperatures	Freezing Time (Minutes)
–40˚F	22
–100˚F	12
–200˚F	7

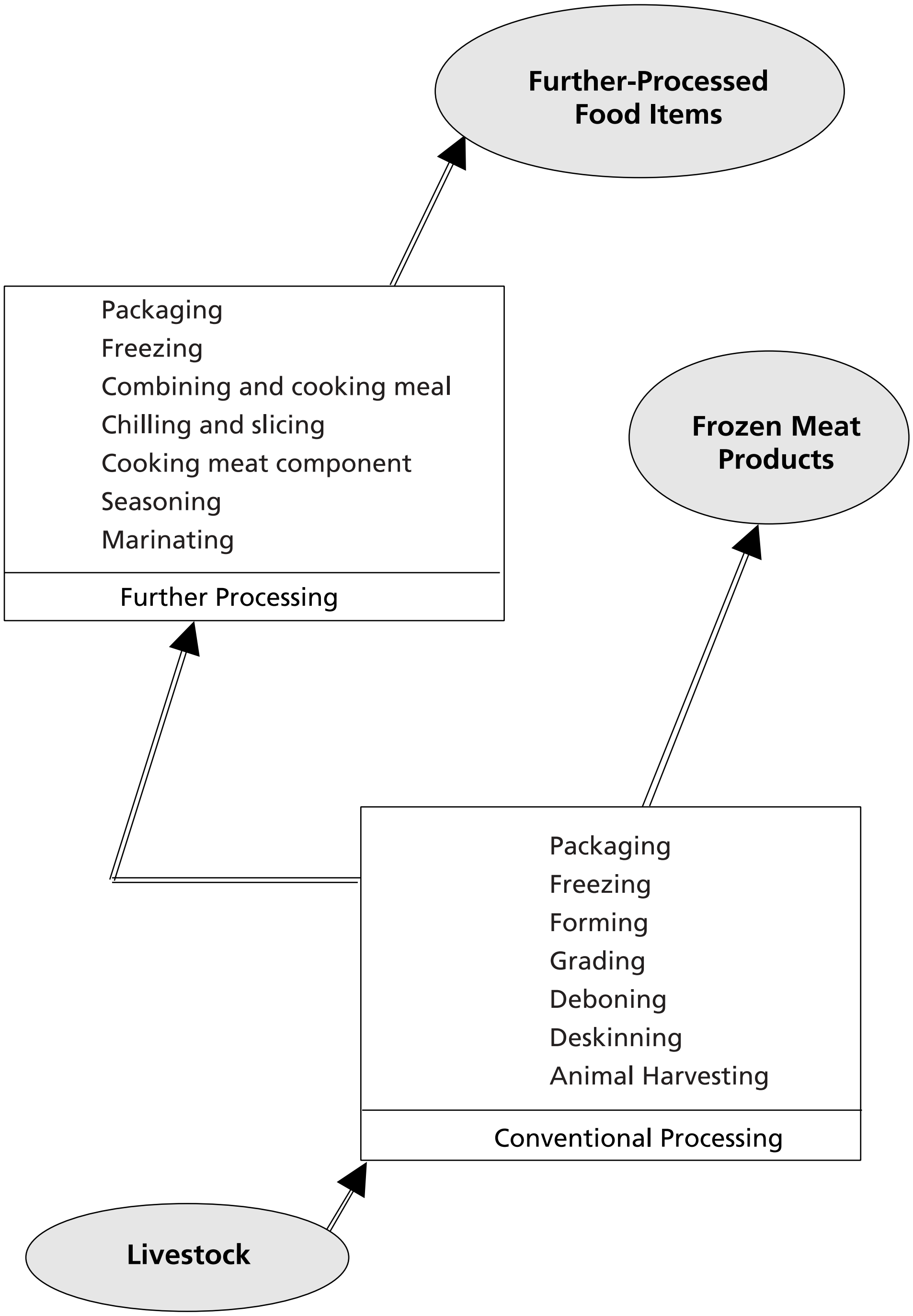
Source: Air Products and Chemicals, Inc., 1998 Dehydration Model Study

Dehydration occurs as water vapor evaporates from hot cooked foods. Rapid freezing reduces dehydration (that is, loss of water content), resulting in juicier and more tasty food. Reduced dehydration also leads to reduced weight loss. Since food items are sold on the basis of weight, this means higher sales.

Manufacturing Further-Processed Foods

Further-processing plants are linked to meat and poultry processing. Plants fall into several categories: conventional animal harvesting plants, further-processing plants, and integrated facilities. Figure 5 describes and charts these processes.

Figure 5. Manufacturing Further Processed Meat Products



- In a conventional animal harvesting plant, livestock and poultry are stunned, slaughtered, washed, de-boned, skinned, chilled, cut up, weighed, and graded, subjected to product forming in tumblers and presses, frozen, and packaged for shipment.
- In further processing plants, meat and poultry parts, received from animal harvesting plants, are seasoned, marinated, and processed through cooking lines. Precooked and ready-to-eat products are then chilled for slicing, possibly combined with other ingredients, refrigerated in freezers, packaged, and shipped.
- In integrated plants, animal harvesting and further processing are combined in one facility.

Poultry Processing Plants

In the early 1990s poultry processing operations were limited to slaughter, cut up, grading, freezing, and packaging.

Reflecting the intensity of market demand for improved convenience, food safety, quality, and labor saving efficiencies, by 1998, 64 of the 239 processing plants of top U.S. broiler companies had cooking lines or were fully dedicated to further processing operations (*Broiler Industry*, 1998).

A large further-processed poultry plant operates at throughput levels as high as 20,000 pounds per hour, two shifts or 16 hours per day, five days per week, and 52 weeks per year, with annual throughput levels of 83 million pounds.

ADVANTAGES OF CCAR TECHNOLOGY IN FURTHER-PROCESSED FOOD MANUFACTURING

After food items are precooked, it is beneficial to chill these items quickly to avoid weight loss through evaporation, quality loss through dehydration, and food safety problems.

Current refrigeration technologies have practical limitations relative to providing cost-effective quick-chill applications.

- For temperatures colder than –70°F, mechanical refrigeration systems will not be suitable. For temperatures between –40°F and –70°F, mechanical systems require expensive customization.
- Cryogens, hauled in from regional air separation and carbon dioxide plants, provide ultra-cold temperatures for rapid chilling and freezing, but costs per pound of items being chilled or frozen are twice the cost of CCAR and four times the cost of mechanical refrigeration.

CCAR's ultra-cold (–70˚F to –50˚F) temperatures facilitate rapid chilling and freezing of food items more cost effectively than mechanical or cryogenic refrigeration systems.

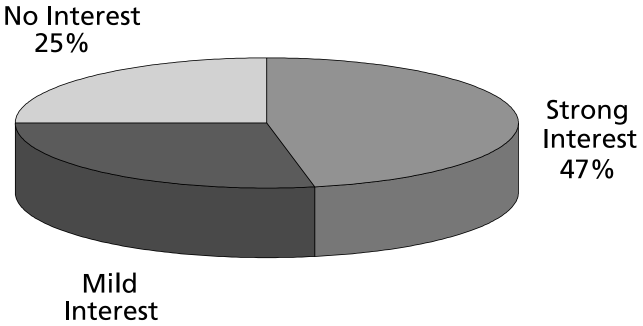
Estimated Market Demand for CCAR

To confirm that food industry market drivers (Figure 3) can translate into commercial opportunities for CCAR technology systems, Air Products initiated two market studies over the 1996–1999 period. An outside study was commissioned to Strategex, an independent market research company. Strategex surveyed 23 companies in the food processing industry and 10 in the film and tape industries. The study indicated that 20 percent of respondents placed a high value on refrigeration services colder than –40°F, lending support to the proposition that the ultra-cold CCAR could have attractive commercial potential.

An Air Products internal study surveyed 36 food companies. The results are shown in Figure 6. Forty-seven percent expressed strong interest in the CCAR technology, "if it could deliver ultra-cold refrigeration at reduced cost, relative to cryogens." Twenty-eight percent expressed mild interest.

> "Further processing plants are a key target market for CCAR."
>
> Air Products and Chemicals, Inc., 2000.

Figure 6. Survey of Food Companies' Interest in CCAR Technology



Source: Unpublished Air Products internal study, 1999.

The Strategex study also indicated that 54 percent of respondents would be willing to outsource refrigeration services to an external contractor. Given that Air Products' established practice is to sell refrigeration on the basis of "sale of refrigeration" contracts, rather than "sale of equipment" contracts, this was a significant finding.

From a food processor's point of view, CCAR "sale of refrigeration" contracts represent the outsourcing of internal utility services. Air Products would install CCAR units adjacent to food processing plants, own, operate, and maintain these CCAR units, and sell refrigeration services "over the fence" under a long-term contract.

> Downsizing in the food industry is cited as the driving force behind outsourcing.
>
> *Food Engineering,* 2000.

Air Products did not separately investigate CCAR's export market potential. However, based on extrapolating the company's experience, it was concluded that aggregate overseas demand was likely to approximate U.S. demand levels.

Air Products recently signed a memorandum of understanding with a major U.S. meat processor for the commercial placement of a 200-ton capacity CCAR system. In addition, negotiations are reportedly underway for selling CCAR services to other major food processors. The memorandum of understanding tends to validate the conclusions of the above market research studies and indicates a strong potential for CCAR market acceptance.

Pathways to Markets

Five promising pathways have been identified for marketing CCAR services to the food processing industry. These pathways reflect industry trends and conditions relative to the modernization and expansion of food processing manufacturing plants.

Food Industry Plant Modernization and Expansion

While demand for refrigerated meats, poultry, and further-processed foods is projected to grow, industry profitability is expected to drop.
Reflecting depressed profitability and constrained capital budgets, the recent food industry Plant Construction Survey indicates a preference for less expensive and "quicker to implement" plant modernization and plant expansion projects over more expensive and "longer-to-implement" greenfield projects. The survey indicates that of "753 food processing capital construction projects in 1999, 68 percent involved expansions and renovations and 32 percent resulted in greenfield construction" (Young, 2000).

Liquid Nitrogen Cryogen Replacement Pathway. It is estimated that there are 700 liquid nitrogen–based refrigeration customers in the U.S. food industry. Most have small production levels. It is expected that one or two of the larger liquid nitrogen customers would shift to CCAR technology each year. Each CCAR unit would produce 200 tons of output and would be built adjacent to the food processing plant. Air Products would own and operate these units and deliver refrigeration service "over the fence" on a sale of refrigeration basis.

Carbon Dioxide Cryogen Replacement Pathway. About 1,500 U.S. food processing plants utilize carbon dioxide-based refrigeration systems. Again, most have small production levels. It is estimated that one or two of the larger carbon dioxide plants would shift to CCAR-based refrigeration each year. And again, the CCAR unit would produce 200 tons of refrigeration output and would sell refrigeration service "over the fence" on a sale of refrigeration basis.

Capacity Boost Pathway. The third pathway is to install CCAR units at further-processed food plants with expanding production. In the current climate of "modest profitability among publicly traded processors," plant expansion is the likely approach for increasing production levels (Broiler Industry, 1998). The CCAR unit would complement the plant's existing mechanical refrigeration system. The food processor would pay for only the incremental refrigeration services during a gradual production ramp-up. CCAR's "good turndown characteristics, i.e., its ability to operate efficiently at less than full load" will reduce energy costs and facilitate the processor growing into CCAR's full capacity. It is estimated that one or two food plants will contract for sale of refrigeration-based CCAR services each year.

Greenfield Pathway. The fourth pathway is to install CCAR units at newly constructed food plants. It is estimated that one processing plant will contract for CCAR services each year.

Export Pathway. Given the additional challenges of generating overseas sales with new technology, export sales of CCAR services are estimated to start in the third year of an active marketing program. Projected CCAR installations at overseas food processing plants is one unit in 2004, three units in 2005, and four units in 2006.

SECONDARY MARKETS FOR CCAR

Potential applications for CCAR technology have been identified in other markets besides food processing. These secondary markets include volatile organic compound recovery systems as well as applications in the liquid natural gas, pharmaceutical and petrochemical industries. Secondary market opportunities are summarized in Table 4.

Volatile Organic Compounds Recovery and Liquid Natural Gas Industry Trends and Pathways

VOLATILE ORGANIC COMPOUNDS RECOVERY SYSTEMS

Chemicals containing hydrogen, carbon, and other elements that evaporate easily are known as volatile organic compounds (VOCs). In the presence of sunlight and nitrogen oxides, VOCs react to form ground level ozone, a component of smog. Sources of man-made VOCs include auto and diesel emissions, petrochemical industry emissions, and emissions from the use of solvents and coatings. VOC emissions are regulated by the U.S Environmental Protection Agency and state air quality boards. These regulations drive the VOC recovery and abatement market, whose annual revenues are projected to reach $4.3 billion (*Power Engineering*, 2000).

The use of refrigeration and condensation to capture VOCs represents one approach for controlling these harmful emissions. Other approaches include incineration and membrane adsorption. CCAR can provide the refrigeration component for the VOC condensation approach and would provide the environmental benefit of using high-pressure air as the refrigerant. Air Products has a strong market position in the specialty chemical and petroleum

Table 4. Secondary Market Opportunities for CCAR

Secondary markets	*Applications*	*Competing technologies*
Volatile organic compound recovery (50-ton CCAR units)	Refrigeration used to condense and separate volatile organic compound gases	Incineration and membrane adsorption
Liquid natural gas (200-ton CCAR units)	Replace marine diesel fuel	Compressed natural gas and low sulfur diesel
	Peak shaver in remote locations, without sufficient pipeline capacity	Compressed natural gas and expanded natural gas pipeline system
Pharmaceutical (10-ton CCAR units)	Freeze drying and controlling low temperature reactions	—
Petrochemical (200-ton CCAR units)	Storage and process refrigeration	Propane and other hydrocarbon refrigerants

industries (which generate considerable VOC emissions). These business relationships are expected to facilitate market acceptance of CCAR as a viable and environmentally attractive volatile organic compound recovery technology.

Although a formal market assessment remains to be completed, VOC recovery applications are estimated to generate annual sales of refrigeration revenues of $250,000 each. This application is expected to require smaller CCAR units sized at 50 tons of refrigeration rather than the standard 200-ton units.

LIQUID NATURAL GAS APPLICATIONS

Natural gas is composed of methane and ethane and may contain water, hydrogen sulfide, carbon dioxide, and other impurities. It is cleaned and processed into pipeline quality "dry gas" at gas processing plants. A national network of 70,000 miles of high-pressure pipelines is used to transport gas to U.S. retail markets.

When cooled to a temperature of –260°F at atmospheric pressure, gas condenses to liquid natural gas. Under higher pressures, natural gas can be liquefied at warmer temperatures.

Under 200 psig of pressure, CCAR units will liquefy natural gas at –150˚F (i.e., within the unit's cooling range).

When natural gas is liquefied, the resulting liquid natural gas is 600 times more compact than gas in a vapor state, giving 1.7 gallons of liquid natural gas the equivalent energy density of a gallon of diesel fuel (Sen, Gas Technology Institute (Interview)). Liquefaction can thus facilitate ease of storage and transportation when pipelines are not available or when storage space is constrained.

U.S. liquid natural gas consumption is sourced from domestic liquefaction facilities and from overseas imports. Imports in 1999 at three East coast marine terminals and one West coast marine terminal were 160 billion cubic feet. Annual liquid natural gas imports are projected to grow fivefold by 2015 and reach 900 billion cubic feet, reflecting growing demand projections (Sen, Gas Technology Institute (Interview)).

LIQUID NATURAL GAS MARINE PROPULSION

According to research conducted at Carnegie Mellon (Corbet and Fischbeck, 2000), air emissions from cargo ships and ocean-going ferries powered by diesel engines are among the most polluting combustion sources per ton of fuel consumed. Multiple regulatory initiatives are underway. The International Maritime Organization is expected to implement new NOX reduction regulations. The European Union is expected to set tougher limits on marine fuel sulfur levels (Environmental News Service, 2000). Under authority of the 1990 Clean Air Act, the U.S. Environmental Protection Agency is developing regulations for emissions from diesel powered marine engines (Hughes, 1999).

Use of CCAR to liquefy pipeline natural gas potentially enables replacement of diesel fuel with liquid natural gas for selected marine applications. This could generate considerable environmental benefits. At port facilities, CCAR units would provide refrigeration to liquefy pipeline natural gas. Port terminals are expected to require three CCAR units of 200 tons of refrigeration each. The liquid natural gas would be stored in insulated bulk tanks onboard ferries, barges, and other ocean-going vessels and for use as alternative fuel to marine diesel.

Ferries and barges are expected to operate on a two-shift, seven-day-per-week basis and generate $840,000 annual sale of refrigeration revenues for each CCAR unit. Annual sale of refrigeration revenues from CCAR are estimated at $2.5 million for a liquid natural gas liquefaction facility operating with three CCAR units.

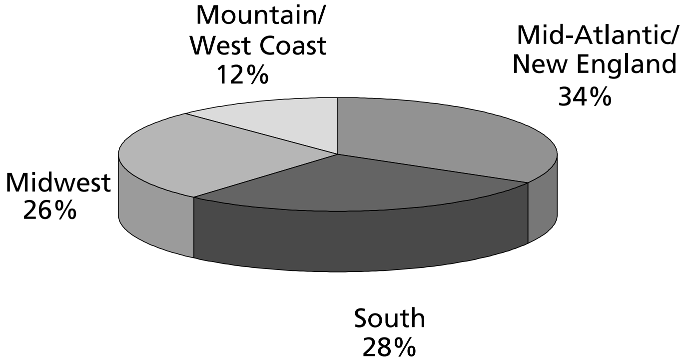
When pressurized to 200 psig as required to produce liquid natural gas at –150°F , use of CCAR will require heavier storage tanks with thicker walls. This may negatively affect the economics of utilizing CCAR-generated liquid natural gas on ocean-going vessels. Will pressurized liquid natural gas maintain its advantages relative to compressed natural gas when storage tank wall thickness and weight are considered? Technical studies and a formal market assessment remain to be completed.

LIQUID NATURAL GAS PEAK SHAVER

To meet normal demand levels, natural gas distribution companies obtain gas supplies from a network of high pressure pipelines that cross much of the United States. To meet unusual peak demands, distribution companies may store natural gas in refrigerated liquid natural gas form. Liquid natural gas takes up 1/600th of the required space for gas in a vapor state. CCAR systems could potentially be used to provide the required ultra-cold refrigeration for conversion of gas to liquid form at newly constructed liquid natural gas peak shaving facilities.

According to Chicago Bridge & Iron Co., U.S. gas distribution companies are currently operating 57 liquid natural gas peak shavers for meeting peak demand conditions. Nineteen are in the mid-Atlantic and New England region, sixteen in the South, fifteen in the Midwest, and seven in Mountain states and the West coast. Figure 7 depicts the geographic distribution of liquid natural gas peak shavers.

Figure 7. **Geographic Distribution of 57 Liquid Natural Gas Peak Shavers in the United States**



Source: Unpublished data from Chicago Bridge & Iron Co, 2000.

Forty-seven (82 percent) of U.S. peak shavers were built during the 1960s and 1970s. Only five were built in the 1980s and five in the 1990s. It would appear that the market for peak shavers has fallen off as national pipeline capacity continues to grow and to provide gas transportation services effectively to more and more regions of the country. New construction of liquid natural gas peak shavers may be restricted to regions with limited pipeline capacity and thus may represent only a limited niche market for CCAR systems.

Each peak shaving facility using CCAR is expected to require three CCAR units with 200 tons of refrigeration capacity. These units would be sold outright to natural gas distribution companies on the basis of sale of equipment contracts. Expected one-time revenues from the sale of three CCAR units are estimated to be $6.0 million.

OTHER POTENTIAL APPLICATIONS

The following pathways have been identified as possible opportunities for CCAR units through discussions with Air Products staff and with industry experts.

1. Pharmaceutical industry: Pharmaceutical companies have expressed interest in using CCAR technology for freeze-drying formulations, low temperature chemical reactions, and volatile organic compound collection and recycling. The industry needs more cost-effective low-temperature refrigeration for these processes, and CCAR could be cost competitive with currently utilized cryogenic systems.

   Prior to CCAR's acceptance by the pharmaceutical industry, several market barriers must be overcome. First, units must be scaled down to 20 tons of refrigeration, a tenfold reduction from the standard 200-ton size. Scaling down is likely to require significant additional R&D effort. In addition, use of CCAR technology will raise regulatory issues. The pharmaceutical industry is regulated by the U.S. Food and Drug Administration. The introduction of a new refrigeration technology may constitute a modification of FDA-approved manufacturing practices and necessitate a potentially costly and time-consuming review and approval process. A formal assessment of CCAR's pharmaceutical market potential should be undertaken before committing resources to further R&D and commercialization efforts.

2. Petrochemical industries: The chemical, petrochemical, and oil refinery industries utilize large refrigeration plants for (1) separation of one gas from another by liquefying one gas, (2) capturing and condensation of gases as an alternative to wasteful or environmentally impermissible venting, (3) maintenance of stored liquids at low temperatures to control pressure in containment vessels, and (4) removal of the heat of chemical reaction in manufacturing process. These industries currently utilize mechanical refrigeration systems with hydrocarbon (propane, ethane, and ethylene) refrigerants. These refrigerants are nearly "cost free" byproducts of petrochemical manufacturing and are considered to have good refrigerant properties.

   Given that mechanical systems have a lower first cost and that refrigerants like propane often come "cost free" to petrochemical companies, CCAR may not currently be cost competitive for petrochemical applications (Kiczek, Air Products; Shepherd, Toromont (Interview)). However, the petrochemical industry is under substantial regulatory pressure on environmental issues and substituting air-based CCAR could appear to be "low hanging fruit" in achieving positive environmental results. Air Products reported on-going discussions with potential CCAR clients in the petrochemical industry who were interested in utilizing air rather than polluting hydrocarbons as refrigerants.

UNLIKELY MARKETS

In its 1995 proposal to ATP, Air Products mentioned potential market opportunities in the residential and automotive refrigeration markets. The 1995 proposal postulated that "with further technical advances in equipment and efficiency, the residential, automotive, and other warmer temperature applications may become viable markets" for CCAR technology.

To reach these markets, the ATP-funded CCAR technology would have to undergo fundamental design changes to scale down 200-ton units to the micro scale typical of residential and automotive applications.

4 Economic Impact

ASSUMPTIONS

Target industry market analysis was used to define assumptions for quantifying the economic benefits of the Advanced Technology Program (ATP) funded closed-cycle air refrigeration (CCAR) technology over the period 2002–2016.

We projected impacts over the period for a Base Case Scenario and an Optimal Scenario. The Optimal Scenario posited deployment of approximately 20 percent more CCAR units than the Base Case Scenario.

The Base Case Scenario posited that 17 CCAR units (200 tons of refrigeration each) would be installed and operating over a 15-year implementation period (Table 5). Of the 17 units,

- Ten units were assumed to replace liquid nitrogen or carbon dioxide cryogenic refrigeration systems. The U.S. food industry has an installed base of 700 liquid nitrogen and 1500 carbon dioxide systems.
- Seven units were assumed to boost mechanical refrigeration capacity at existing food processing plants and at newly constructed greenfield plants. Ninety percent of the $131 billion U.S. further-processed food industry uses onsite mechanical refrigeration systems.

Table 5. Base Case Projections for Number of U.S. Food Industry CCAR Installations

Pathways	*2002*	*2003*	*2004*	*2005*	*2006*
Replacing liquid nitrogen or carbon dioxide cryogenic refrigeration	1	2	2	2	3
Boosting or replacing mechanical refrigeration	0	1	2	2	2
Total U.S. units	1	3	4	4	5
Cumulative units	1	4	8	12	17

The Optimal "Stretch" Scenario posited that 21 CCAR units would be deployed and operating over a 15-year implementation period, a 23 percent increase over the Base Case. It assumed that 12 units would be installed as liquid nitrogen or carbon dioxide replacements and 9 units would be installed to boost existing mechanical systems or to displace new mechanical systems in greenfield construction projects (Table 6). Appendix A further documents the basis for these assumptions.

Table 6. Optimal Case Projections for Number of U.S. Food Industry CCAR Installations

Pathways	*2002*	*2003*	*2004*	*2005*	*2006*
Replacing liquid nitrogen or carbon dioxide cryogenic refrigeration	1	2	3	4	2
Boosting or replacing mechanical refrigeration	0	2	2	1	4
Total U.S. units	1	4	5	5	6
Cumulative units	1	5	10	15	21

Price Assumptions

Retail prices for further-processed foods vary from $4 to $9 per pound in 2001. For food sold in restaurants and other food service establishments, prices to the ultimate customers can exceed $9 per pound. For our analysis, we made the conservative assumption that the 2001 price per pound of further-processed food is $5 per pound.

Displacement of Mechanical Systems

The use of CCAR technology instead of mechanical refrigeration enables faster freezing. Faster freezing improves food *quality*. There is less dehydration. Food is juicier and more tasty. To estimate broad-based economic benefits from improved food quality, we posited that improved quality would lead to a $0.25 per pound increase in price above the $5 per pound baseline. Relative to the current range of retail prices ($4–$9) and relative to observable price elasticity levels, a $0.25 adjustment for improved quality was deemed to be conservative. Quality benefits not captured by the food processing industry through higher prices will be passed on to end consumers.

Faster chilling and faster freezing also result in *reduced yield loss* (weight loss) in food processing. The technical literature indicates that faster freezing can lead to as much as 7 percent yield improvement. However, yield characteristics are affected by a complex range of variables, including the texture of food items, the thickness of food items, cooking temperatures, and the type and age of equipment. Given the variability of manufacturing parameters we posited conservatively that CCAR would result in a 2 percent yield improvement over mechanical refrigeration.

To estimate the economic value of avoided yield loss, Air Products assumed that CCAR units would be installed at intermediate-to-large food processing plants, each with approximately 10,000 pounds of hourly product throughput, equivalent to 41,600,000 pounds of annual throughput. Consistent with industry practice, we specified that each 200-ton CCAR unit would operate two shifts, five days each week, 52 weeks per year, and generate $600,000 of annual sale of refrigeration revenues.

In addition to improving food processing yield and the quality of cooked food items, faster freezing could lead to *increased production rates*. While the speed of manufacturing lines is a function of many variables, including the type and age of equipment, manufacturing processes, and levels of product demand, faster freezing could reduce bottlenecks in the freezing process and facilitate additional production volume. We posited that throughput would increase by 1 percent as a result of using CCAR instead of mechanical refrigeration and that incremental revenues would generate a 10 percent contribution to pre-tax net income.

Average operating costs are expected to be higher for CCAR than for mechanical refrigeration. Based on discussions with food industry and refrigeration industry experts, average operating costs were estimated to be $.02 per pound of processed food for CCAR in comparison with $.01 for mechanical refrigeration.

Displacement of Liquid Nitrogen and Carbon Dioxide Cyrogens

Where CCAR technology displaces cryogen refrigeration, CCAR does not provide additional quality, yield, or production rate benefits. Liquid nitrogen and carbon dioxide cryogens already facilitate rapid chilling and freezing, with the associated quality, yield, and production benefits, but at twice the cost of CCAR. The economic benefit of using CCAR is lower cost by about $.02 per pound of processed food throughput.

ATP Investments and Adjustment for Inflation

Over the 1996–1998 period, ATP invested $2.1 million in the CCAR project. To adjust for inflation in the subsequent cash flow analysis, ATP's investments were normalized to 2001 dollars using a 3 percent annual inflation rate over the 1996–2000 period (Table 7). Benefit cash flows were likewise normalized to 2001 dollars using an average inflation rate of 3 percent for the period 2002–2016.

Table 7. ATP Investment Normalized to 2001 Dollars

	Nominal ATP investment	*Normalized 2001 dollars*
1996	743,000	861,342
1997	813,000	915,038
1998	551,000	602,092
1999	0	0
2000	0	0
2001	0	0

CCAR Export Sales

Historically, Air Products' total international sales for refrigeration services have approximated domestic sales levels. Commensurately, Air Products anticipates that international CCAR sales will approach domestic sales levels, but subject to some delay. Given the absence of formal market studies for overseas demand and of significant international marketing activity to date, it was assumed that first export sales would be delayed until 2004. Subsequent, overseas sales were estimated to be one CCAR unit in 2004, three units in 2005, and four units in 2006.

QUANTITATIVE BENEFITS TO THE U.S. ECONOMY

Cash Flow Time Series

Base Case Scenario cash flows are summarized in Table 8. (See Appendix B for details.) Table 8 indicates that food quality and yield improvements from replacing mechanical refrigeration systems with CCAR provided the lion's share of CCAR's induced economic benefits, reaching a high point in 2006 of approximately $73 million per year from quality improvements and $28 million per year from yield improvements.

Public Returns: Net Present Value, Internal Rate of Return, and Benefit-to-Cost Ratio

Estimated cash flows for the Base Case Scenario and Optimal Scenario were used to compute several projected measures of the public return from ATP's investment in CCAR technology development: net present value, internal rate of return, and benefit-to-cost ratio. They are summarized in Tables 9 and 10. (See Appendices B and C for details.) The net present values of separate benefit components were computed along with the total net present value. The component measures for the Base Case Scenario are included in Table 9 and for the Optimal Scenario in Table 10.

Among the component measures, CCAR-induced quality improvements had the greatest economic impact, representing 66 percent of the total $459 million net present value benefit

Table 8. Base Case Cash Flows from Improved Quality, Yield, and Production Rates and from Reduced Refrigeration Costs

	CCAR replacement of mechanical systems			*CCAR replacement of cryogenic systems*	
	Cash flow from quality improvement	*Cash flow from yield improvement*	*Cash flow from higher production*	*Cash flow from cost reduction*	*Combined cash flow*
		(Millions 2001 dollars)			
1996					–0.8610
1997		Investment years			–0.9150
1998					–0.6020
1999					0
2000					0
2001 e					0
2002 e	0	0	0	0.832	0.8320
2003 e	10.4	3.952	0.2184	2.496	17.0664
2004 e	31.2	11.856	0.6552	4.160	47.8712
2005 e	52.0	19.760	1.0920	5.824	78.6760
2006 e	72.8	27.664	1.5288	8.320	110.3128
2007 e	72.8	27.664	1.5288	8.320	110.3128
2008 e	72.8	27.664	1.5288	8.320	110.3128
2009 e	72.8	27.664	1.5288	8.320	110.3128
2010 e	72.8	27.664	1.5288	8.320	110.3128
2011 e	72.8	27.664	1.5288	8.320	110.3128
2012 e	72.8	27.664	1.5288	8.320	110.3128
2013 e	72.8	27.664	1.5288	7.488	109.4808
2014 e	62.4	23.712	1.3104	5.824	93.2464
2015 e	41.6	15.808	0.8736	4.160	62.4416
2016 e	20.8	7.904	0.4368	2.496	31.6368

in the Base Case Scenario. Yield improvements contributed 25 percent while faster production rates contributed only 1 percent to the total net present value. Cost savings from displacing liquid nitrogen and carbon dioxide with CCAR contributed 7 percent to net present value.

As with the Base Case Scenario, the Optimal Scenario showed the bulk of economic benefits coming from replacing mechanical refrigeration systems, through quality and yield improvements, and through faster production.

Table 9. Base Case Net Present Value, Internal Rate of Return, and Benefit-to-Cost Ratio

	Replacing mechanical systems			*Replacing cryogenic systems*	
	Economic impact of improved quality	*Economic impact of improved yield*	*Economic impact of faster production*	*Economic impact of reduced cost*	*Combined economic impact*
Net present value (million)	$301	$113	$4	$33	$459
Internal rate of return					83%
Benefit-to-cost ratio					220:1

Table 10. Optimal Scenario Net Present Value, Internal Rate of Return and Benefit-to-Cost Ratio

	Replacing mechanical systems			*Replacing cryogenic systems*	
	Economic impact of improved quality	*Economic impact of improved yield*	*Economic impact of faster production*	*Economic impact of reduced cost*	*Combined economic impact*
Net present value (million)	$387	$146	$6	$41	$585
Internal rate of return					90%
Benefit-to-cost ratio					280:1

A comparison of the Base Case Scenario and Optimal Scenario indicates that economic impact according to the net present value measure was roughly proportional to the number of installed CCAR units. The Optimal Scenario had a 23 percent higher number of installed CCAR units than the Base Case Scenario and generated a 22 percent higher net present value and 27 percent higher benefit-to-cost ratio. Internal rates of return do not behave in a linear manner and changed by only 8 percent for the Optimal Scenario.

Increased U.S. Exports

The ATP-funded CCAR technology development is expected to generate significant incremental U.S. exports over the 2004–2016 time period. Average Base Case annual export revenues for CCAR are estimated at $4.8 million dollars. Average Optimal Scenario annual export revenues are estimated at $6 million dollars.

Private Benefits

Air Products has intellectual property rights to CCAR technology under existing patents and can thereby control the sale and installation of CCAR units for the next 14 years. Future benefits to Air Products in the form of incremental revenues and profits provide their key motivation for marketing the CCAR technology and reaching beyond the food processing industry. The resulting CCAR sales are the vehicle by which Air Products' customers and consumers will realize economic benefits from improved quality, yield, production rates, and reduced operating costs in food processing and other industries.

To assess Air Products' motivation to move the CCAR technology forward, we estimated incremental revenue streams corresponding to the Base Case Scenario, as shown in Table 11.

Discounting revenue streams in Table 11 at 9 percent (a likely proxy for the cost of funds of a major U.S. corporation), the present value of projected revenues from CCAR installations in the food processing, volatile organic compound recovery and liquid natural gas markets was projected to be $64.8 million. For the Optimal Scenario, the present value of revenue streams was projected to be $66.9 million. In the absence of proprietary information about Air Products' internal cost structure, it was not possible to estimate CCAR's actual profit contributions.

QUALITATIVE BENEFITS

Broad-Based Benefits to Food Processing Industry: Improved Food Safety

Food safety concerns have resulted in increased demand for fully cooked product. However, food items, even if fully cooked can grow bacteria in the 40°F to 141°F temperature range, the so called "danger zone." CCAR is an innovative refrigeration technology that can

Table 11. Air Products Revenue Streams from Base Case

	Cumulative CCAR units U.S. and overseas	*Estimated revenues sale of refrigeration ($ million)*
2002 e	1	0.6
2003 e	5	3.0
2004 e	12	7.2
2005 e	22	13.2
2006 e	35	21.0
2007 e	35	21.0
2008 e	35	21.0
2009 e	35	21.0
2010 e	35	21.0
2011 e	35	21.0
2012 e	35	21.0
2013 e	34	20.4
2014 e	30	18.0
2015 e	23	13.8
2016 e	13	7.8

accelerate the rate of cooling of hot, cooked, further-processed foods and facilitate passing through the "danger zone" quickly, thereby minimizing food safety concerns.

Cryogenic refrigeration (liquid nitrogen and carbon dioxide) can also be used to accelerate "falling through the danger zone." However, liquid nitrogen and carbon dioxide systems achieve this benefit at four times the cost of conventional mechanical refrigeration and at twice the cost of CCAR technology. As such, the CCAR technology promises to be a cost-effective enabling technology for promoting food safety in the manufacturing process of precooked, further-processed foods.

Broad-Based Benefits to Food Service Industry: Improved Food Safety and Reduced Costs

The food service industry is subject to Hazard Analysis and Critical Control Points (HACCP) food safety regulations, requiring labor-intensive monitoring of food items during the time interval between cooking and getting temperatures down to safe levels. When food service establishments replace previously uncooked food with precooked, further-processed foods, the need to bring food temperatures to cooking levels is eliminated, reducing labor requirements for HACCP compliance. Cost savings from reduced labor requirements can improve the operating economics of the food service industry and contribute to its continued economic vitality and growth.

Broad-Based Benefits to Food Processing Industry: Reduced Harmful Emissions

At the time of the 1995 proposal to ATP, it was anticipated that CCAR technology would displace mechanical refrigeration systems that use CFC and other ozone depleting refrigerants. This expectation is unlikely to be realized. Many industrial refrigeration systems have already been converted from CFC and other ozone-depleting refrigerants to ammonia-based systems (Andersen, International Institute of Ammonia Refrigeration; Shepherd, Toromont; Stellar Group (Interview)). In addition, the economics of CCAR technology are attractive only in the –70°F to –150°F operating range, not in the warmer operating range of mechanical refrigeration applications.

While impact in the form of CFC reduction is unlikely to materialize, a different pathway for reducing harmful emission can now be identified where CCAR provides distributed refrigeration through refrigeration units located at the site of use. By replacing liquid nitrogen and carbon dioxide cryogens with CCAR, diesel emissions from hauling cryogens to the site of use can be entirely avoided. The beneficial emissions impact of eliminating cryogen transportation can be substantial over the 10-year operating life of each CCAR unit. With 42 million pounds of annual production, each food processor would utilize over 8 million gallons of cryogen. Diesel powered trucks, each holding 7,000 gallons, would make 1,200 round-trips to meet cryogen demand from one food processing plant. Across 10–12 plants deploying CCAR units, 12,000–14,000 annual round trips can be avoided.

Broad-Based Benefits to Liquid Natural Gas Industry: Reduced Marine Diesel Emissions

According to recent research (Corbet and Fischbeck, 2000), air emissions from cargo ships and ocean-going ferries powered by diesel engines are among the most polluting combustion sources per ton of fuel consumed. These findings are prompting vigorous regulatory activity. The International Maritime Organization is expected to implement new nitrogen oxide reduction regulations. The European Union is expected to set tougher limits on marine fuel sulfur levels. Under the 1990 Clean Air Act, the U.S. Environmental Protection Agency is developing regulations to reduce emissions from diesel-powered marine engines.

Replacing diesel fuel with natural gas (in the form of liquid natural gas) for selected marine applications is expected to provide considerable environmental benefits. A March 2000 study conducted by Commonwealth Scientific Research Organization (Cope and Katzfey, 1998) referenced emission levels for heavy duty transport vehicles running on diesel fuel and natural gas. Natural gas-fired engines had significantly lower carbon monoxide, nitrogen oxide, and particulate (PM10) emissions than diesel engines. Hydrocarbon emissions from gas-fired engines were higher than diesel engines. However, this could be remedied by utilizing catalysts. Findings are summarized in Table 12.

Table 12. Emission Characteristics of Natural Gas–Fueled Transportation Vehicles Versus Diesel-Fueled Vehicles

	Emission rates (grams/km)			
	CO	*NO_X*	*HC*	*PM10*
Existing fleet	33.00	22.00	3.70	1.00
Low sulfur diesel	1.20	14.00	0.87	0.11
Natural gas	0.66	9.90	3.61	0.05
Natural gas*	0.71	7.20	9.82	0.01

Note: CO, carbon monoxide; NOx, nitrogen oxide; HC, hydrocarbons.
Source: Cope and Katzfey, 1998; *Motta et al., 1996.

Assuming heavy duty road transport emission statistics provide an appropriate surrogate for large marine diesel engines, a comparison of emission rates of natural gas with other fuel sources suggests that conversion to liquid natural gas could result in a 98 percent reduction of carbon monoxide emissions , 55 percent reduction in nitrogen oxide emissions, and 95 percent reduction of particulates.

Broad-Based Benefits for Volatile Organic Compound Recovery Industry

Volatile organic compound (VOC) emissions are regulated at the federal and state levels. These regulations drive the U.S. VOC recovery and abatement market. The VOC abatement market is projected to reach revenue levels of $4.3 billion (*Power Engineering*, 2000). If CCAR were to provide a novel and economically viable VOC refrigeration technology, it could then contribute to increased competition within the VOC abatement industry. Increased competition could lead to higher efficiency levels and lower VOC emissions over time. Estimating VOC-related benefits would require a formal market study and is beyond the scope of this work.

CROSS-INDUSTRY KNOWLEDGE DIFFUSION

After Air Products received the CCAR patent in 1996, new technical knowledge was developed during the subsequent ATP-funded project, making it possible to reach step-out performance levels with

- Low leakage compressor shaft dry gas seals
- Heat exchanger fabrication methods for high pressure tolerances
- Cost effective casting technology, utilizing Quick Cast honeycomb structures

The substantial performance improvements associated with the design and fabrication of these system components were recognized by *Chemical Engineering Magazine* when CCAR was chosen as a finalist for the 1999 Kirkpatrick Award. Additional dissemination of information about CCAR's step-out performance characteristics is likely to lead to expanded utilization of low leakage seals, high pressure heat exchangers, and honeycombed investment casting technologies in other industries. These innovations and associated opportunities for cross-industry knowledge diffusion and use beyond the CCAR technology are described in Appendix B.

ENHANCED ORGANIZATIONAL CAPACITY

As a result of the CCAR development experience, both Air Products and Toromont reported enhanced organizational capabilities.

- Air Products Cryomachinery Laboratory started using advanced computational fluid dynamics methodologies for routine design of expander turbines.

- Toromont reported the formation of a subsequent strategic alliance with Allison Chalmers Compressors to develop and market the API 617 Refrigeration System. Toromont indicated that its ATP-funded, successful joint venture with Air Products provided the experience and inclination to enter into the new strategic alliance with Allison Chalmers.

5 Conclusions

In 1995, Advanced Technology Program (ATP) funded a joint venture project, involving Air Products and Chemical, Inc., and Toromont Process System, Inc., to design, fabricate, and pilot test closed-cycle air refrigeration (CCAR), a new form of industrial refrigeration that uses environmentally benign dry air as the working fluid.

CCAR was developed as a cost effective technology for the ultra-cold –70°F to –150°F temperature range. Development and successful pilot test were completed in 1999. The CCAR technology is currently in an active marketing phase and generating considerable interest for food processing, marine propulsion, and petrochemical industry applications.

The primary markets for CCAR deployment will be the $131 billion further processed and ready-to-eat segments of the U.S. food industry. In these rapidly growing segments, CCAR is poised to provide:

- Improved food safety through rapid freezing of precooked processed foods
- Improved food quality and food processing yields
- Reduced environmental emissions from diesel-powered road transportation of liquid nitrogen and other cryogenic material.

Based on primary research and analysis completed during 2000 and early 2001, the case study projects a substantial public return on ATP's investment in CCAR technology:

- Benefit-to-cost ratio of 220:1 to 280:1 (Base Case versus Optimal Scenario)
- Net present value of $459–$585 million (2001 dollars)
- Internal rate of return of 83–90 percent
- $5–6 million incremental U.S. export sales each year
- 12,000–14,000 truck deliveries of cryogens (and associated diesel emissions) avoided each year

Beyond food processing, the CCAR technology has significant potential for deployment in the volatile organic compound recovery industry, the liquid natural gas industry, and the pharmaceutical and petrochemical industries. One example of prospective deployment in the above markets is the utilization of CCAR technology for liquid natural gas marine terminals that supply natural gas to ocean-going vessels. Displacing marine diesel fuel with natural gas is expected to result in 98 percent reduction in carbon monoxide, 55 percent reduction in nitrogen oxide, and 95 percent reduction in particulate emissions.

The case study concludes that the new CCAR technology has made significant progress toward meeting the necessary conditions for commercialization and market acceptance. These conditions are the:

- Successful completion of technical development and demonstration phases
- Market studies indicating substantial demand in the food processing industry
- Informal market intelligence indicating good potential in the volatile organic compound recovery, liquid natural gas, pharmaceutical, and petrochemical industries
- Technological advantages that can be translated into business advantages
- Active marketing of CCAR systems by Air Products

Based on the above elements of progress, the study further concludes that the anticipated public returns from ATP's investment in CCAR technology, the broad-based economic benefits to the food processing industry and consumers, and the substantial environmental benefits from avoided refrigerant emissions and transport emissions have a high probability of being realized.

Owing to Air Products' assessment of project risk and their earlier decision to de-prioritize the development of a high-risk CCAR technology, it is unlikely that CCAR technology would have been developed without ATP funding. As a result, the above benefits can be directly attributed to the ATP investment.

6 Glossary

ATP	Advanced Technology Program, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce
BTU	British Thermal Unit, measure of heat energy
CAD	Computer-aided design
CCAR	Closed-cycle air refrigeration
CFC	Chlorofluorocarbon, ozone depleting substances, used as a refrigerant in mechanical refrigeration systems; phased out under Montreal Protocol
CHE	Chart Heat Exchanger
CO	Carbon monoxide
CO_2	Carbon dioxide, in solid state, frequently used as cryogenic medium in food freezing process
Compander	(Com)pressor and Ex(pander) mounted on the same shaft; part of the power requirements of the compressor is provided by expander and part from an electric motor, geared to the common shaft
COP	Coefficient of performance: a measure of refrigeration cycle efficiency; defined as useful refrigeration output in kW divided by the electrical input in kW
Cryogenics	Technology for producing temperatures lower than normal industrial refrigeration, that is, according to some lower than –70°F and according to others lower than –150°F
DGS	Dry gas seals

EPA	U.S. Environmental Protection Agency
Expander	Cryogenic turbine that expands and cools a gas stream
Evaporator	Component of a mechanical refrigeration system, also known as a load heat exchanger; the evaporator is a vessel where high pressure liquid refrigerant vaporizes to a gaseous state: refrigeration of an enclosed space (load) is achieved when liquid refrigerant withdraws heat energy from the load as it changes to a gaseous state; withdrawal of heat energy is based on the principle of latent heat of evaporation
°F	Degrees Fahrenheit, temperature measurement scale
Greenfield	New construction of manufacturing plants
HACCP	Hazard Analysis and Critical Control Points: a category of U.S. Food and Drug Administration food safety regulations, and requires labor-intensive monitoring of cooking processes in food processing plants and in food service establishments
HC	Hydrocarbons, a standard category of engine emission pollutant
HCFC	Hydro-chlorofluorocarbon: ozone depleting substance used as a refrigerant in mechanical refrigeration systems; to be phased out under the Montreal Protocol
Heat exchanger, Heat transfer coil	Devices that transfer heat from a hot to a cold fluid; the barrier between the two fluids is a metal wall, such as that of a tube or pipe. In many engineering applications it is desirable to increase the temperature of one fluid while cooling another. This double action is economically accomplished by coils, evaporators, condensers, and coolers that may collectively be considered heat exchangers
HP	Horse power: a unit of measurement for the power output of machinery, such as an internal combustion engine, used in marine vessel propulsion
HX	Heat exchanger
Joule-Thompson effect	Scientific principle indicating that the temperature of a gas stream will be reduced while passing through a very small nozzle

Latent heat of evaporation	Heat energy required to bring about phase change from liquid to gaseous form, at constant temperature; it is the amount of energy that must be absorbed or withdrawn form the refrigeration load, by a liquid refrigerant, to change its phase to a gaseous state
LIN	Liquid nitrogen
LNG	Liquid natural gas
Load	Refrigeration load of a mechanical or cryogenic refrigeration system; heat energy that must be withdrawn by the system to reduce temperatures in a refrigerated chamber to specified levels
Mechanical refrigeration	Also known as vapor compression refrigeration; motor-driven compressor impels the circulation of refrigerant through a closed loop; mechanical refrigeration is achieved when liquid refrigerant withdraws heat energy from the load as it changes to a gaseous state
MOU	Memorandum of understanding
OMB	Office of Management and Budget
NH_3	Ammonia, common refrigerant in industrial mechanical vapor compression systems; ammonia is toxic.
NO_X	Nitrogen oxides
PM10	Particulate emissions
PSIG	Pounds per square inch gauge; measure of system pressure
Refrigerant	Working medium in a refrigeration cycle that is successively compressed, cooled, and then expanded; in expanding, the refrigerant absorbs heat from its surroundings to provide refrigeration
Refrigeration	Withdrawal of heat from a chamber (refrigeration load) to achieve temperatures lower than ambient temperatures; after heat is withdrawn from refrigeration load it is transferred to a condenser and dissipated to air or water coolant
SOE	Sale of equipment

SOR	Sale of refrigeration; Air Products would build, own, and operate CCAR units adjacent to customers' industrial facility and sell refrigeration services "over the fence" on the basis of a long-term contract
Spiral freezer	Freezer for chilling and freezing food where a continuous belt, carrying food items through the refrigerated enclosure, is stacked in a spiral arrangement up to 50 tiers high; allows very long belts and long food product residence time in a compact freezer space
Sublimation	Carbon dioxide can sublimate, or change directly from frozen solid state to gaseous state, without going through an intermediate liquid phase
3-D	Three-dimensional
Ton of refrigeration	Measure of refrigerating capacity, sufficient to freeze (bring about phase change from liquid to solid state) a ton of water; The origin of this term suggests the early history of refrigeration in ice plants: 1 ton refrigeration capacity ice plant could freeze 2,000 pounds (or 1 ton) of ice, corresponding to 12,000 BTU per hour
Tunnel freezer	Freezer for chilling and freezing food, where a continuous belt, carrying food items through the refrigerated enclosure, makes a single straight line pass through refrigerated enclosure; belt may be perforated, permitting vertical flow of refrigerated air through the belt and product layer
Turndown	Operating equipment under less than full load; equipment with good turndown characteristics can be operated efficiently at less than full load
VOC	Volatile organic compound: chemicals containing hydrogen, carbon, and other elements that evaporate easily; in the presence of sunlight and nitrogen oxides, VOCs react and form ground level ozone, a component of smog

7 Interviews

Air Products and Chemicals, Inc.
- Edward Kiczek – CCAR Project Manager
- William Roberts – Marketing Manager, Food Industry
- Joseph Kugler – Manager, Cryomachinery
- Mike Tomasic – Cryoengineering
- Bill Brown – Cryoengineering
- Andrew Struble – Cryoengineering
- Philip Winkler – Manager, Government Systems

Air Conditioning and Refrigeration Institute
- Glenn Hourahan – R&D Department

American Society Heating, Refrigeration and Air-Conditioning Engineers
- William Sicton – Director of R&D

Brett & Wolff
- Everett Brett, Ph.D. – Principal
- John Wolff – Principal

British Columbia Ferry Corporation
- Robert Hamilton – Vice President

Chart Heat Exchangers
- Dan Markussen – Sales Engineer

Chicago Bridge & Iron
- Don Coers – LNG Marketing Manager
- Jon Hagstrom – VP Technology

Food Engineering Magazine
- Chuck Morris – Midwest Editor

FlowServe
- Mark Klossek – Sales Engineer

Gas Technology Institute
- Dr. Coleen Sen – Vice President

International Institute of Ammonia Refrigeration
- Kent Anderson – President

Eastman Kodak Co.
- Tim White – CCAR Pilot Project Engineer

U.S. Maritime Administration
- Daniel Gore

Sterling Group

TNO Department of Refrigeration & Pump Technology
- S. M. VanderSluis – Department Head
- Marcel Verschoor – JOULE II Project Manager

Toromont Process Systems, Inc.
- James Shepherd – Vice President

U.S. Department of Agriculture, Economic Research Service
- Leland W. Southard

U.S. Coast Guard
- Daniel Leubecker
- Wayne Lundy

8 References

American Frozen Food Institute. 2000, October 24. *Industry at a Glance.* [On-line] Available: <http://www.affi.com>

American Meat Institute. 2000. *Role of Meat and Poultry Industry in the U.S. Economy.* [On-line] Available: < http://www.meatami.com>.

Barbosa-Canovas, Gustavo, and Vega-Mercado, Humberto. 1996. *Dehydration of Foods.* New York: Thompson.

Broiler Industry. 1998. Survey Highlights: Nation's Broiler Industry. (January): 18–60.

Bylinsky, Gene. 1998. Industry's Amazing Instant Prototypes. *Fortune* 137(1): 120–123.

Cope, M. E., and Katzfey, J. J. 1998. *Air Quality Impact of the Perth Bus Fleet* (SB/1/376). Aspendale, Australia: Commonwealth Scientific Research Organization.

Corbet J., and Fischbeck, P. 1997. Emissions From Ships. *Science* 278 (October): 823–831.

Environmental News Service. 2000, October 19. Europe Warned to Limit Sulfur in Marine Fuels.

Erickson, Marilyn C., and Hung, Yen-Con. 1997. *Quality of Frozen Food.* New York: Chapman and Hall.

Hughes, J. 1999. EPA Turns Regulatory Eye on Air Pollution by Ferries. *Detroit News,* July 28.

Morris, Chuck. 2000. The State of Food Manufacturing, 2000. *Food Engineering* 72(9): 71–84.

Motta, R., Norton, P., Kelly, K., Chandler, K., Schumacher, L. and Clark, N. 1996. *Alternative Fuel Transit Buses* (Report NREL/TP-425-20513) Golden, CO: National Renewable Energy Laboratory.

National Restaurant Association. 2001. *2001 Restaurant Industry Forecast* [On-line] Available: < http://www. restaurant.org/research/forecast.html>.

Palumbo, Anne. 2000. The Case for Outsourcing. *Food Engineering* 72(February): 65–72.

Power Engineering. 2000. VOC Market to Top $4.3 Billion by 2004. 104(3): 12.

Progressive Grocer. 1999. 1999 *Annual Report* [On-line] Available: <http://www.progressivegrocer. com/annualreport.htm>.

Refrigerated & Frozen Food Processor. 2000, October. Food Report. [On-line] Available: <http://bevindustry.com/rff/>.

Refrigerated Foods. 2000, June. [On-line] Available: <http://www.refrigeratedfrozenfood.com>.

Technology Review. 1998, September/October. Heavy Metal—Quickly. 101(5): 17.

Valentas, Kenneth, and Rotstein, Enrique. 1997. *Handbook of Food Engineering Practice*, Boca Raton, FL: CRC.

Young, Renee. 2000. 2000 Plant Construction Survey. *Food Engineering* 72(4): 71–74.

9 Related Reading

Air Products and Chemicals, Inc., 2000. *1999 Annual Report.* Allentown, PA: Air Products and Chemicals, Inc.

Air Products and Chemicals, Inc., 2000. *CCAR Breakthrough Technology for Food Freezing.* Allentown, PA: Air Products and Chemicals, Inc.

Air Products and Chemicals, Inc., 1999. *Proprietary Internal Study on Dehydration Modeling and Test Results.* Allentown, PA: Air Products and Chemicals, Inc.

American Society of Heating, Refrigeration, Air-Conditioning Engineers (ASHRAE). 1994. *1994 Handbook: Refrigeration Systems and Applications.* Atlanta: American Society of Heating, Refrigeration, Air-Conditioning Engineers.

Austin, G. T. 1994. *Shreve's Chemical Process Industries.* New York: McGraw-Hill.

Barron, Randall F. 1985. *Cryogenic Systems.* New York: Oxford University Press.

Beer, T., Grant, T., Brown, R., Edwards, J., Nelson, P., Watson, H., Williams, D. 2000, March. *Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles: Stage 1.* Aspendale, Australia: Commonwealth Scientific Research Organization.

Brett, Everett, C. 1998, May. LNG as a Fuel for a High Speed Sealift Vessel. Office of Sponsored Engineering Programs, University of Alabama.

Chicago Bridge & Iron Co., 2000, October. *LNG Peak Shaving Facilities.* Chicago: Chicago Bridge & Iron Co.

Christensen, Clayton, M. 1997. *The Innovator's Dilemma.* Cambridge, MA: Harvard Business School Press.

Coers, D. 1996. World's First LNG Vehicular Fuel Production Plant. Paper presented at American Gas Association Operations Conference, May 19–22. Montreal, Quebec.

Desrosier, Norman, and Tressler, D. K. 1997. *Fundamentals of Food Freezing.* Westpoint, CT: AVI.

Food Refrigeration & Process Engineering Research Centre (FRPERC). 1994. *Air Cycle Test Rig at TNO*. University of Bristol, UK: Food Refrigeration & Process Engineering Research Centre.

Hands, B. A. 1986. *Cryogenic Engineering*. Orlando, FL: Academic.

Howard, William, and Guile, Bruce. 1992. *Profiting From Innovation: The Report From the National Academy of Engineering*. New York: The Free Press.

Kassicieh, Suleiman, and Radosevich, H. Raymond. 1993. *From Lab to Market: Commercialization of Public Sector Technology.* New York: Plenum.

Kaufman, Mike, ed. 1986. *The Capital Budgeting Handbook*. Homewood, IL: Dow Jones-Irwin.

Kerzner, Harold. 1998. *Project Management: A Systems Approach to Planning, Scheduling and Controlling*. New York: John Wiley.

Lapides, Daniel, ed. 1976. *Encyclopedia of Energy.* New York: McGraw-Hill.

Maxwell, Jennifer. 2000. Evaluation of Potential Diesel Emission Reduction Technologies Available to the British Columbia Ferry Corporation. Unpublished study. British Columbia Ferry Corporation, Victoria, BC.

Singh, P. 1993. *Introduction to Food Engineering*. Orlando, FL: Academic.

Stoecker, W. F. 1998. *Industrial Refrigeration Handbook*. New York: McGraw-Hill.

Strategex, Inc., 1996, June. *Air Products and Chemicals Refrigeration Study.* Strategex, Inc.

U.S. Department of Agriculture. 2000. *Agricultural Baseline Projections to 2009*. Staff Report WAOB-2000-1. Washington, DC: U.S. Department of Agriculture.

U.S. Energy Information Administration. 1998, October. *LNG Fact Sheet*. Washington, DC: U.S. Energy Information Administration.

Urbain, Walter M. 1986. *Food Irradiation*. Orlando, FL: Academic.

Appendix A:
CCAR Technical Characterization

REFRIGERATION TECHNOLOGIES

Refrigeration is the withdrawal of heat from a chamber (refrigeration load) to achieve temperatures lower than ambient temperatures. After heat is withdrawn, it is transferred to a condenser and dissipated to air or water.

The purpose of refrigeration in food processing is to preserve quality and delay spoilage; in volatile organic compounds recovery, is to condense and capture harmful vapor emissions; and in the liquid natural gas industry, to facilitate natural gas storage and transportation.

CCAR was developed as an innovative refrigeration technology for the above industrial applications in the –70°F to –150°F ultra-cool range. Above –70°F, mechanical refrigeration takes over as the predominant technology. Under –150°F, refrigeration is provided by cryogenic methods.

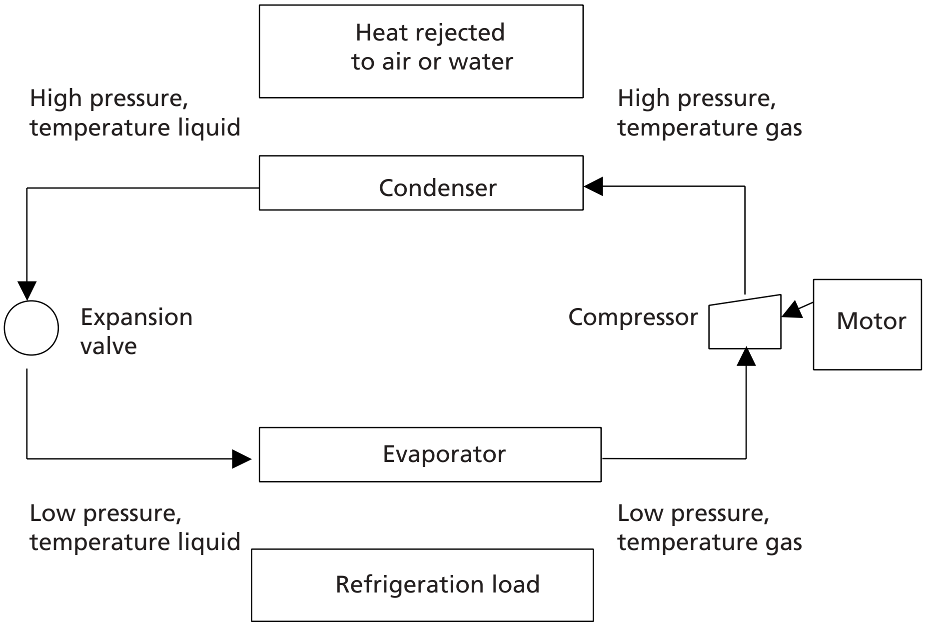
Mechanical Refrigeration

More than 90 percent of U.S. industrial refrigeration is provided by mechanical systems using ammonia as the refrigerant (Shepherd, Toromont; Anderson, International Institute of Ammonia Refrigeration; Sterling Group (Interview)). Mechanical refrigeration units are dedicated systems, installed at individual industrial facilities and owned and operated by the industrial companies.

Refrigeration is achieved when the refrigerant, circulating in the system, withdraws heat energy from the chamber to be cooled (load). Heat energy (latent heat of evaporation) is absorbed as liquid refrigerant undergoes a phase change to a gaseous state. Systems are composed of four basic elements connected with piping into a closed loop that re-circulates refrigerant (Figure A1).

Compressors (generally) use motor-driven rotating impellers to generate gas pressure. Gaseous refrigerant enters the compressor at low pressure and temperature and exits at high pressure and temperature.

Figure A1. Conventional Mechanical Refrigeration System



Inside condenser coils gaseous refrigerant condenses to liquid state. To facilitate phase change, the condenser dissipates heat energy to ambient air or water. High pressure refrigerant exits at lower temperature.

An expansion valve controls the flow of high pressure liquid refrigerant to the evaporator. As refrigerant passes through the expansion valve it is further cooled by the Joule Thompson effect, the scientific principle that the temperature of a stream is reduced when forced through a narrow nozzle and allowed to expand.

Inside the evaporator, liquid refrigerant vaporizes into a gaseous state. Vaporization requires heat energy, which is extracted from the industrial process load (food items to be cooled). The refrigerant is returned to the compressor to repeat the cycle.

Cryogenic Refrigeration

The cryogenic approach uses very low temperature gases in liquid or solid form such as liquid nitrogen or solid carbon dioxide. Liquid nitrogen is manufactured in large, capital-intensive air separation plants, serving entire geographic regions and hauled to distant points of use in insulated tanks via ground transport. carbon dioxide is manufactured as part of fertilizer production or directly extracted from the ground. Solid carbon dioxide is hauled to points of use via ground transport. The carbon dioxide market is deemed to be approximately twice the size of the liquid nitrogen market. About 25 percent of cryogens in the United States go into food processing applications. (Kiczek, Air Products (Interview)).

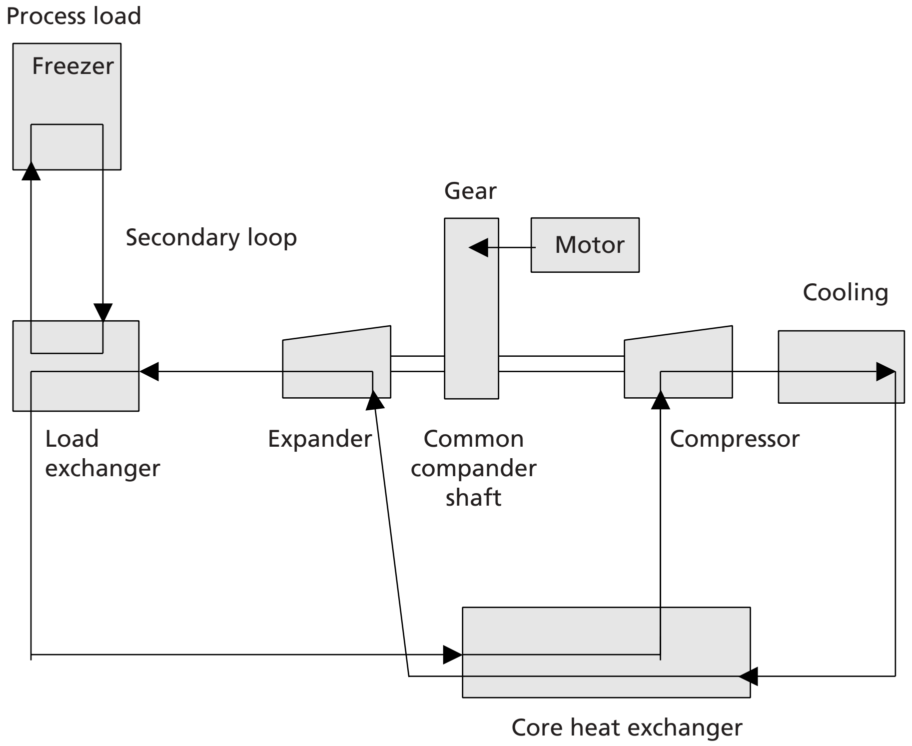
At industrial plants, cryogens can be released into freezer coils or into freezer chambers, coming into direct contact with items to be refrigerated.

The cost of cryogenic refrigeration is four times the unit cost of mechanical refrigeration, and cryogenic refrigeration is generally used only for specialty applications requiring temperatures colder than –100°F.

Closed-Cycle Air Refrigeration

CCAR is a new refrigeration technology, combining elements of mechanical and cryogenic refrigeration in an innovative manner. It operates on the reverse Brayton Cycle and uses dry, high pressure air as the working fluid. It is configured as a closed system to avoid the need for continuous moisture removal from makeup air; that is, moisture would freeze on turbine blades and ice particles could damage the rotating equipment. The high-pressure working fluid is in a gaseous state throughout the system, and, unlike mechanical refrigeration, phase change and the latent heat of evaporation are not utilized. For a functional representation of the CCAR system, see Figure A2.

Figure A2. CCAR System



As with mechanical refrigeration, the compressor raises air pressure and temperature. The cooling system acts like a water-cooled condenser to remove the heat of compression. As an additional step to pre-cool the air stream, air passes through a core heat exchanger to give up heat energy to the cold air stream returning from the load exchanger.

Pre-cooled high-pressure air then enters the expander, which is a rotating machinery that looks like a small turbine. It is used to extract energy from the air stream by reducing pressure, thereby resulting in a temperature drop from –82°F to –105°F. The air stream applies a force to the expander blades, causing the rotation of the compander shaft and providing some of the power requirements of the compressor. The compressor's remaining power requirements are met by an electric motor, geared to the compander shaft.

Cold air from the expander flows to the load exchanger. If the load is adjacent to the CCAR unit, then the load exchanger can directly cool the space to be refrigerated. If the process load is hundreds of feet away (as in many food industry applications), then a low pressure secondary loop is used to connect the CCAR unit to the process load. The reason for the secondary loop is economics. It is too expensive to run thick-gauge stainless steel piping to deliver high-pressure cold air to distant refrigeration loads.

In the load exchanger, cold air picks up heat energy from process load or from the secondary loop (in contact with process load) and exits as return-air at –90˚F. Return air is taken through the core heat exchanger and is returned to the compressor to repeat the cycle.

Using modified design parameters, the expander can produce temperatures as low as –184˚F. However, at temperatures colder than –150˚F, CCAR is no longer cost competitive with cryogenic systems.

KODAK DEMONSTRATION

The CCAR testing program included bench tests at Air Products' Cryomachinery Laboratory and a nine-month demonstration program at a Kodak facility in Rochester, New York. The demonstration unit was operated for 6,000 hours, reaching or exceeding design specifications.

- Unit output was specified at 50 tons of refrigeration. The plant operated at 60 tons, exceeding the design point by 20 percent.

- System reliability was targeted at 95 percent. The plant operated at 98 percent, exceeding expectations by 3 percent.

- Refrigeration temperatures were maintained within a close (+/–2°F) band around the –100°F design point.

- At –70°F the demonstration unit achieved a 0.75 coefficient of performance level, consistent with coefficient of performance levels of conventional mechanical refrigeration units. The coefficient of performance COP measures the relative efficiencies of different refrigeration cycles. At –100°F, a temperature level that conventional mechanical refrigeration units cannot reach, the unit operated at the 0.66 coefficient of performance design point.

- With 40 percent turndown (load reduction), CCAR unit efficiency (coefficient of performance) decreased by only 3 percent. Comparable 40 percent turndown of a conventional mechanical refrigeration unit resulted in 37 percent efficiency reduction.

- At less than 85 decibels, Occupational Safety and Health Administration requirements were met.

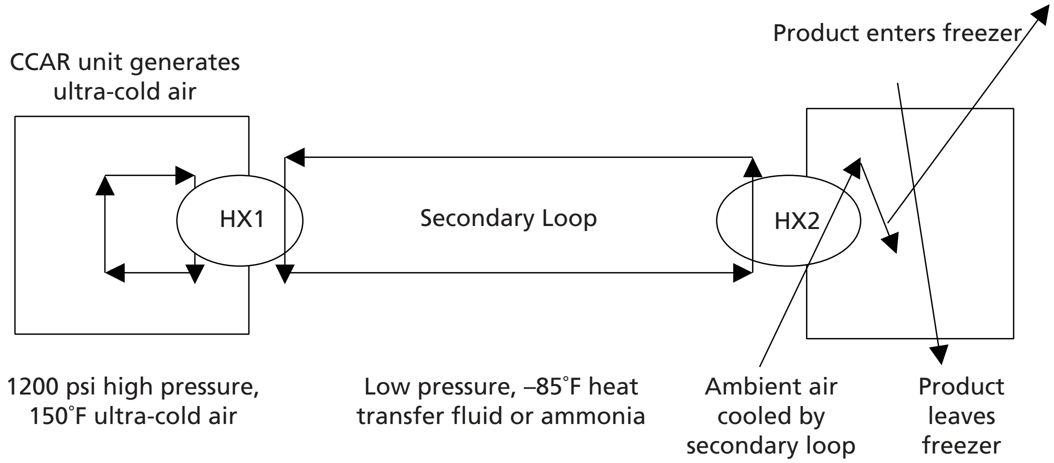
The overall assessment by Kodak Project Manager (W. Klumpp) was that "CCAR met or exceeded all acceptance criteria, as set forth in our contract" and that the test was a successful demonstration of CCAR's technical feasibility.

CCAR CONFIGURATION IN FOOD PROCESSING

Air Products has developed a standard CCAR unit for food industry applications, sized at nominal 200 tons of refrigeration capacity, optimizing cost-performance relationships. The unit is pre-assembled and skid mounted. It has a footprint of 12 by 40 feet and can be placed outside food processing plants to save plant space. It weighs about 125,000 pounds.

Food processing refrigeration loads (high volume items, moving on continuous belts) may be hundreds of feet from the CCAR unit. Hence, food industry applications typically require a secondary loop that can efficiently transport cooling to process loads. Unlike the high pressure (1200 psig) CCAR loop, the secondary loop is operated at low pressures (around 10–15 psig) using smaller diameter and thinner wall piping. Secondary loops deliver refrigeration to process loads through heat transfer coils (HX1 and HX2) to spiral freezers, tunnel freezers, and other "enabling devices." Figure A3 displays this configuration.

Figure A3. **Food Processing Plant CCAR Configuration**



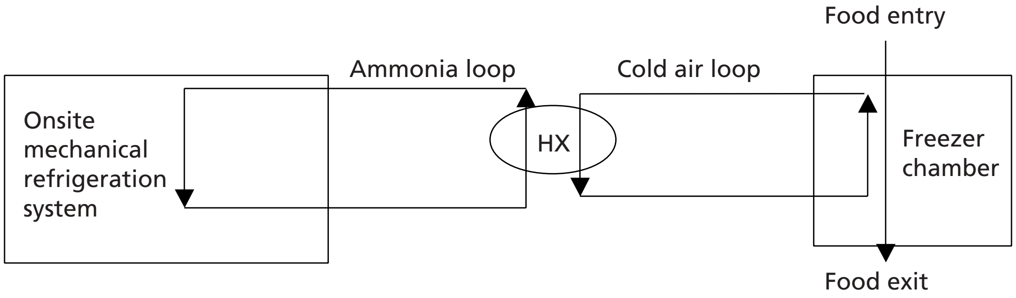
For initial CCAR systems (to be installed in further-processed food plants), Air Products plans to use ammonia as the secondary loop heat transfer fluid. The choice of ammonia creates some limitations. It becomes highly viscous at –90°F and cannot be used under –95°F. Hence, CCAR effective temperature range, with an ammonia-based secondary loop, is reduced from its full economic potential of –150°F down to –95°F. Ammonia is also toxic and this compromises CCAR's environmental and safety "credentials." However the impact is one of appearance more than substance, as the CCAR secondary loop is hermetically sealed under only one atmosphere of internal pressure (in contrast to mechanical refrigeration systems, where ammonia is under higher pressures, causing potential leakages at compressor shaft seals). As part of a continuing CCAR technical development effort, Air Products is evaluating alternative heat transfer fluids to replace ammonia, including D-Limonene^{TM}, a harmless chemical made from citrus extracts.

Food Freezing Systems

Chilling and freezing products in further-processing plants takes place in a variety of freezing systems, otherwise known as "enabling devices" (Valentas and Rotstein, 1997).

When coupled with mechanical refrigeration, the refrigeration effect is transmitted from the ammonia (working fluid) through heat transfer coils (HX) to an air stream that circulates throughout the freezing chamber by the action of fans (Figure A4).

Figure A4. Food Processing Plant with Mechanical Refrigeration



Freezing systems or chambers, used with mechanical refrigeration, include:

- Spiral freezers, for large volume production where food items are placed on continuous metal conveyor belts, passing through the chamber via a spiral path.

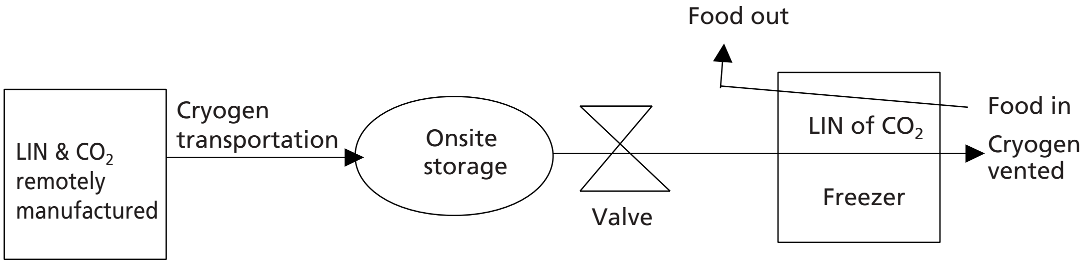
- Tunnel freezers, for both small and large production volumes. Small volume operations can grow by installing additional modules. Product moves through the freezing chamber on a continuous linear conveyor.

- Impingement freezers, increasing heat transfer rates by higher air velocity. Process is more energy intensive but still less expensive than cryogenic freezing. Over the last five years, impingement freezing (augmenting conventional mechanical refrigeration systems) was developed to achieve improved quality and yield and reduced dehydration of hamburger patties.

- Fluidized bed freezers are a specialized tunnel freezer where high velocity air flow is directed upward through perforations in the belt, causing small unwrapped products of uniform size and shape (fries, peas, beans, etc.) to be suspended in the air. Freezing is faster and more uniform.

When coupled with cryogenic refrigeration (utilizing liquid nitrogen or carbon dioxide), freezers are customized so that vaporized liquid nitrogen or carbon dioxide come into direct contact with food items to extract large amounts of heat (see Figure A5).

Figure A5. Food Processing Plant with Cryogenic Refrigeration



Entering spiral and tunnel freezers, cryogens pass through throttling valves so as to expand to atmospheric pressure and vaporize. Liquid nitrogen, vaporized to cold nitrogen gas, is sprayed into freezers to freeze food items via direct contact. Nitrogen gas (initially at –320˚F) moves through progressively warmer zones and may be re-circulated throughout the freezer prior to being vented. Freezers can operate at temperatures as low as –150˚F to –200˚F. carbon dioxide passes through the throttling valves to be sprayed on food products as a mixture of solid (dry ice) and vapor. The sublimation of solid carbon dioxide to vapor provides part of the refrigeration effect, with the remainder deriving from cold vapor entering the chamber directly.

Sublimation is the direct transformation from a solid to a gaseous state.

When coupled with hybrid cryomechanical refrigeration, specialized freezer systems are needed. Cryomechanical freezing starts with liquid nitrogen or carbon dioxide being used to freeze the crust and to seal the surface of food items so as to prevent loss of internal moisture. Next, food items are moved to another freezer where cold air from mechanical refrigeration system completes the freezing process. The complexity of multiple freezers, conveyors, and cryogen storage facilities significantly increases cryomechanical costs over conventional mechanical refrigeration. However, improved food quality and reduced yield loss compensate for higher freezing costs. Table A1 compares CCAR with alternative systems.

Table A1. **Comparison of Freezing Systems**

	Mechanical				*Cryogenic*		*Hybrid*	*CCAR*
	Spiral freezer	*Tunnel freezer*	*Impingement*	*Fluidized bed*	*Special spiral*	*Special tunnel*	*Cryo-mechanical*	
Capital cost	I / H	I	I / H	I	L	L	I	L
Operating cost	I	I	I	I	H	H	I / H	I +
Freezing rate	I	I	I / H	I / H	H	H	H	H

Notes: L, low; I, intermediate; H, high. Cryogenic and CCAR rankings are based on sale of refrigeration-type service contract.
Source: Valentas and Rotstein, 1997.

Plant Throughput and Refrigeration Capacity

For a very large further-processing poultry plant, throughput can be as high as 20,000 pounds per hour. The plant would typically run for two shifts or 16 hours per day, five days per week. Prior to freezing and packaging the product, the meat would be marinated, cooked, chilled (to facilitate slicing), sliced, for instance, into fajitas strips, mixed with other meal items, such as vegetables and oils, and cooked.

About 200 BTU of heat content would be withdrawn from each pound of cooked hot product to lower its temperature to 10°F. Handling 20,000 pounds per hour would require a refrigeration system producing 4 million BTU/hour and a plant capacity of 334 tons of refrigeration (Roberts (Interview)). Two standard CCAR units of 200 tons would be installed to support this level of production.

For a large poultry processing plant, we assumed 10,000 pound per hour production and the installation of one 200-ton CCAR unit.

INNOVATIONS FROM CCAR DEVELOPMENT

To make CCAR a practical refrigeration alternative, efficiency and reliability levels had to be improved and costs reduced relative to the cost of cryogenics. The coefficient of performance

(COP) is the key measure for efficiency. To achieve COP levels in the 0.66–0.75 range, CCAR process optimization required using

- High pressure (1,200 psig) air, in combination with –150°F temperatures and 30,000 rpm compander shaft speeds. In combination, these were challenging "step out" conditions, requiring significant technical advances.
- Single wheel compressor and single wheel expander designs, compared to more expensive cryogenic systems with multi-staged compressors and expanders.
- Low compression ratios (compressor output to expander output) of 1.6:1 compared with cryogenic machines operating at ratios of 8:1.
- Ultra low leakage seals, to prevent high pressure air escaping at the surface of the compressor and expander shaft at more than two standard cubic feet per minute.
- High efficiency aluminum plate fin core heat exchanger with 2°F to 3°F close approach temperature delta; that is, no more than 2°F to 3°F temperature difference between high pressure air exiting the cooling system and the return air from the load exchanger.

Some of these innovations, developed to address the CCAR "step-out" conditions, have potential usefulness to other industrial applications and represent opportunities for cross-industry knowledge diffusion.

Improved Shaft Seals

Seals are devices that prevent the leakage of fluids along a rotating shaft, when the shaft extends out from the housing enclosure, containing pressurized fluids.

The CCAR compander consists of a compressor and expander on the same shaft.

In the case of a CCAR unit, the expander and compressor are mounted on a common rotating shaft but are enclosed in separate housing. Seals are needed to prevent high pressure air from escaping along the rotating shaft from the expander and compressor housing. Even modest air leakage from a pressurized CCAR unit will cause significant degradation of system performance and efficiency.

Shaft seals usually consist of an elastomer ring bonded to a metallic ring that is a press (tight) fit in the hole of the housing through which the shaft extends. The sealing effect is provided by a lip on the elastomer ring, pressed snugly around the shaft by a helically wound garter spring. When properly designed and installed, the lip rides on a film of lubricant about 0.0001 inches thick. If improperly installed, then the lubricant film can become too thick and the shaft will leak. If the film becomes too thin, then the lip gets hot, and the seal may fail.

Dry gas seals (DGS) address these problems by providing a clearance maintaining mechanism. One face of DGS is etched with spiral contours or grooves. This changes the pressure distribution or repulsive forces between seal faces, tending to counteract out of spec increases or decreases in face clearance. DGS can maintain non-contacting and non-wearing operations despite vibration, temperature variations, and axial shaft motion.

DGS operations depend heavily on properties of the sealed process gas. The presence of solid or liquid impurities may cause DGS face contamination and damage, even disintegration of the rotating seal face. DGS also has very high first cost, inhibiting industry adoption of this step-out sealing technology, for high speed, smaller OD shaft, turbo-machinery.

Successful performance of dry gas seals under the severe CCAR operating conditions (the combination of 1200 psig pressure, –150°F temperature, and 30,000 rpm shaft speed parameters) is expected to promote greater industry acceptance of DGS technology (Klossek, FlowServe (Interview)).

High Pressure Core Heat Exchanger

Heat exchangers are devices that transfer heat from a hot to a cold fluid. The barrier between the two fluids is a metal wall, such as that of a tube or pipe. In many engineering applications it is desirable to increase the temperature of one fluid while cooling another. This double action is economically accomplished by coils, evaporators, condensers, and coolers that may all be considered heat exchangers.

Heat exchangers are designed with various flow arrangements. The concentric tubes design uses one pipe placed inside another. Cold fluid flows through the inner tube and the warm fluid in the same direction through the annular space between the outer and the inner tube. Heat is transferred from the warm fluid through the wall of the inner tube (the so-called heating surface) to the cold fluid. Concentric tube heat exchangers can also be operated in counter-flow, in which the two fluids flow in parallel but opposite directions.

The shell and tube design utilizes a bundle of tubes through which one of the fluids flows. These tubes are enclosed in a shell with provisions for the other fluid to flow through the spaces between the tubes. In most designs of this type, the free fluid flows roughly perpendicular to the tubes containing the other fluid in what is known as a cross flow exchange.

The plate-fin design uses metal sheets brazed together into internal channels to carry warmer fluid stream, which is to be cooled. Fins, brazed to the outside surface of these channels, facilitate faster and more efficient heat transfer to the cold fluid stream on the outside of these channels.

CCAR uses a high efficiency aluminum plate fin core heat exchanger, fabricated by Chart Heat Exchangers (CHE). CHE has the normal capability of fabricating units up to 1,700 psig for a single stream with lower pressure specifications for the other streams (that is, 50–500 psig). The CCAR core heat exchanger was a "step-out" technology in as much as it specified high pressure tolerance (1,200 psig) for all streams. This required that CHE develop new shop practices and fabrication standards for brazing heavier metal stock in complex configuration. (Markusen, Chart Heat Exchangers (Interview)).

CHE sells high pressure heat exchangers primarily in the petrochemical, air separation, and natural gas industries. This market represents estimated worldwide sales of $10–20 million per year, and CHE is the only U.S. supplier with approximately 50 percent worldwide market share. Based on improvements in shop and fabrication practices, deriving from the CCAR experience, CHE estimates 2–5 percent annual increases in market share or $200,000 to $1 million additional revenues for this U.S. corporation (Markusen, Chart Heat Exchangers (Interview)).

Improved Casting Technology

In a casting process, molten metal is forced into a mold and allowed to harden.

Die casting is a mass production process for forming metal objects by injecting molten metal under pressure (from a plunger or piston) into dies or molds.

Investment casting is a high precision technique for forming metal shapes, involving the following process. A gelatin mold is formed around a solid sculptured form. The mold is removed (in two or more sections) from the sculptured form, and the inside of the mold is filled with wax or coated with a layer of wax of the same thickness as that desired for the final casting. Then the outer gelatin mold is removed, and a second mold, of heat-resisting clay, is formed around the wax shell, the interior of which is filled with a clay core. In the "burnout phase" the mass is baked, hardening the clay and melting the wax, which runs off through openings in the outer mold. Then the hardened mold is packed in sand, and molten bronze is poured through the openings to fill the space vacated by the lost wax. The mold is then broken, and the bronze form remains. In modern foundries, plastics are used in place of the wax. The process is used for manufacturing small parts that require minutely precise details.

To fabricate mold prototypes for the CCAR expander wheel, Air Products Cryomachinery Laboratory used investment casting, in conjunction with rapid prototyping.

Conventional prototyping involves fabricating three dimensional (3-D) models from two-dimensional drawings, using subtractive machining processes such as milling, turning, or grinding metal parts. Conventional prototyping requires significant investment in hard tooling, the production of which is time consuming and expensive. Hard tooling is also inflexible. It cannot easily accommodate design changes typical during the design and development process.

Rapid prototyping automates the fabrication of 3-D models. A computer translates the information form CAD drawing into slices of a 3-D object and passes the information to a prototype machine (PM). The PM transforms this information into solid objects by using lasers to shape the physical layers of the 3-D prototype from plastics or powdered metals (Bylinsky, 1998). Rapid prototyping dramatically cuts the time from drawing board to market and provides flexibility for an evolutionary design and development process at lower costs (*Technology Review*, 1998).

To fabricate prototype molds for the CCAR expander, the prototyping machine used a new advanced material (Quick Cast honeycomb structure) instead of plastic or powdered metal. "Quick Cast build styles create quasi hollow parts from specially formulated resin. The liquid resin is drained from the interior regions of the part, leaving a pattern that is approximately 80 percent hollow with a honeycomb configuration. This structure facilitates the internal collapse of the part, without damage to the shell, during the burnout phase of the investment casting process" (<http://www.3d-cam.com>).

The molds for CCAR expander were fabricated using 3-D rapid prototyping technology with Quick Cast honeycombed advanced materials. This innovative approach significantly reduced the time and cost requirements of building prototypes and facilitated the evolutionary development process for optimizing CCAR performance (Tomasic, Air Products (Interview)).

Appendix B: Base Case Calculations

Table B1. Projected CCAR Units, Base Case

Year	*CCAR units placed*	*Cumulative CCAR units*	*Replacing cryogenic refrigeration*	*Replacing mechanical refrigeration*
1996				
1997				
1998				
1999				
2000				
2001 e				
2002 e	1	1	1	0
2003 e	3	4	3	1
2004 e	4	8	5	3
2005 e	4	12	7	5
2006 e	5	17	10	7
2007 e		17	10	7
2008 e		17	10	7
2009 e		17	10	7
2010 e		17	10	7
2011 e		17	10	7
2012 e		17	10	7
2013 e		16	9	7
2014 e		13	7	6
2015 e		9	5	4
2016 e		5	3	2
2017 e		0	0	0

Table B2. Cash Flow From Improved Quality, Base Case

Years	*ATP investment (million $)*	*Cumulative number CCAR units (units)*	*Volume of processed meat (million pounds)*	*Incremental revenues (million $)*	*Cash flow (million $)*
1996	–0.861				–0.861
1997	–0.915				–0.915
1998	–0.602				–0.602
1999	0				0
2000	0				0
2001 e	0				0
2002 e		0	0	0	0
2003 e		1	41.6	10.4	10.400
2004 e		3	124.8	31.2	31.200
2005 e		5	208.0	52.0	52.000
2006 e		7	291.2	72.8	72.800
2007 e		7	291.2	72.8	72.800
2008 e		7	291.2	72.8	72.800
2009 e		7	291.2	72.8	72.800
2010 e		7	291.2	72.8	72.800
2011 e		7	291.2	72.8	72.800
2012 e		7	291.2	72.8	72.800
2013 e		7	291.2	72.8	72.800
2014 e		6	249.6	62.4	62.400
2015 e		4	166.4	41.6	41.600
2016 e		2	83.2	20.8	20.800
2017 e		0	0	0	0
IRR		74%			
NPV @7%	$301 million				

Table B3. Cash Flow From Improved Food Processing Yield, Base Case

Year	*ATP investment (million $)*	*Volume processed meat (millions pounds)*	*2 percent yield loss reduction (million pounds)*	*Value avoided yield loss (million $)*	*Additional cost (c/lb)*	*Incremental cost (million $)*	*Cash flow (million $)*
1996	–0.861						–0.861
1997	–0.915						–0.915
1998	–0.602						–0.602
1999	0						0
2000	0						0
2001 e	0						0
2002 e		0	0	0	1	0	0
2003 e		41.6	0.832	4.368	1	0.416	3.952
2004 e		124.8	2.496	13.104	1	1.248	11.856
2005 e		208.0	4.160	21.840	1	2.080	19.760
2006 e		291.2	5.824	30.576	1	2.912	27.664
2007 e		291.2	5.824	30.576	1	2.912	27.664
2008 e		291.2	5.824	30.576	1	2.912	27.664
2009 e		291.2	5.824	30.576	1	2.912	27.664
2010 e		291.2	5.824	30.576	1	2.912	27.664
2011 e		291.2	5.824	30.576	1	2.912	27.664
2012 e		291.2	5.824	30.576	1	2.912	27.664
2013 e		291.2	5.824	30.576	1	2.912	27.664
2014 e		249.6	4.992	26.208	1	2.496	23.712
2015 e		166.4	3.328	17.472	1	1.664	15.808
2016 e		83.2	1.664	8.736	1	0.832	7.904
2017 e		0	0	0	1	0	0
IRR		57%					
NPV @7%		$113 million					

Table B4. Cash Flow From Food Processing Throughput, Base Case

Year	*ATP investment (million $)*	*Volume processed meat (million pounds)*	*Increased volume by 1 percent (million pounds)*	*Cash flow (million $)*
1996	–0.861			–0.861
1997	–0.915			–0.915
1998	–0.602			–0.602
1999	0			0
2000	0			0
2001 e	0			0
2002 e		0	0	0
2003 e		41.6	0.416	0.2184
2004 e		124.8	1.248	0.6552
2005 e		208.0	2.080	1.0920
2006 e		291.2	2.912	1.5288
2007 e		291.2	2.912	1.5288
2008 e		291.2	2.912	1.5288
2009 e		291.2	2.912	1.5288
2010 e		291.2	2.912	1.5288
2011 e		291.2	2.912	1.5288
2012 e		291.2	2.912	1.5288
2013 e		291.2	2.912	1.5288
2014 e		249.6	2.496	1.3104
2015 e		166.4	1.664	0.8736
2016 e		83.2	0.832	0.4368
2017 e		0	0	0
IRR	18%			
NPV @7%	$4 million			

Table B5. Cash Flow From Replacing Cryogenic Systems, Base Case

Year	*Cumulative cryogenic units replaced (unit)*	*Volume processed meat (million pounds)*	*Avoided cost (c/lb)*	*Cash flow (million $)*
1996				–0.861
1997				–0.915
1998				–0.602
1999				0
2000				0
2001 e				0
2002 e	1	41.6	–2	0.832
2003 e	3	124.8	–2	2.496
2004 e	5	208.0	–2	4.160
2005 e	7	291.2	–2	5.824
2006 e	10	416.0	–2	8.320
2007 e	10	416.0	–2	8.320
2008 e	10	416.0	–2	8.320
2009 e	10	416.0	–2	8.320
2010 e	10	416.0	–2	8.320
2011 e	10	416.0	–2	8.320
2012 e	10	416.0	–2	8.320
2013 e	9	374.4	–2	7.488
2014 e	7	291.2	–2	5.824
2015 e	5	208.0	–2	4.160
2016 e	3	124.8	–2	2.496
2017 e	0	0	–2	0
IRR	40%			
NPV @ 7%	$33 million			

Table B6. Combined Cash Flow, Base Case

A Year	B Cash flow from quality (million $)	C Cash flow from yield loss (million $)	D Cash flow from through put (million $)	E Cash flow cryo replacement (million $)	F Cash flow B+C+D+E (million $)
1996					–0.8610
1997					–0.9150
1998					–0.6020
1999					0
2000					0
2001 e					0
2002 e	0	0	0	0.832	0.8320
2003 e	10.4	3.952	0.2184	2.496	17.0664
2004 e	31.2	11.856	0.6552	4.160	47.8712
2005 e	52.0	19.760	1.0920	5.824	78.6760
2006 e	72.8	27.664	1.5288	8.320	110.3128
2007 e	72.8	27.664	1.5288	8.320	110.3128
2008 e	72.8	27.664	1.5288	8.320	110.3128
2009 e	72.8	27.664	1.5288	8.320	110.3128
2010 e	72.8	27.664	1.5288	8.320	110.3128
2011 e	72.8	27.664	1.5288	8.320	110.3128
2012 e	72.8	27.664	1.5288	8.320	110.3128
2013 e	72.8	27.664	1.5288	7.488	109.4808
2014 e	62.4	23.712	1.3104	5.824	93.2464
2015 e	41.6	15.808	0.8736	4.160	62.4416
2016 e	20.8	7.904	0.4368	2.496	31.6368
2017 e	0	0	0	0	0
IRR		83%			
NPV		$459 million			
PV Investment		($2.10) million			
PV Cash Flow		$460 million			
Benefit:Cost		220 :1			

Appendix C:
Optimal Scenario Calculations

Table C1. Projected CCAR Units, Optimal Scenario

Year	*CCAR units placed*	*Cumulative CCAR units*	*Replacing cryogenic refrigeration*	*Replacing mechanical refrigeration*
1996				
1997				
1998				
1999				
2000				
2001 e				
2002 e	1	1	1	0
2003 e	4	5	3	2
2004 e	5	10	6	4
2005 e	5	15	10	5
2006 e	6	21	12	9
2007 e		21	12	9
2008 e		21	12	9
2009 e		21	12	9
2010 e		21	12	9
2011 e		21	12	9
2012 e		21	12	9
2013 e		20	11	9
2014 e		16	9	7
2015 e		11	6	5
2016 e		6	2	4
2017 e		0	0	0

Table C2. Cash Flow From Improved Quality, Optimal Scenario

Year	*ATP investment (million $)*	*Cumulative number CCAR units (units)*	*Volume of processed meat (million pounds)*	*Incremental revenues (million $)*	*Cash flow (million $)*
1996	–0.861				–0.861
1997	–0.915				–0.915
1998	–0.602				–0.602
1999	0				0
2000	0				0
2001 e	0				0
2002 e		0	0	0	0
2003 e		2	83.2	20.8	20.800
2004 e		4	166.4	41.6	41.600
2005 e		5	208.0	52.0	52.000
2006 e		9	374.4	93.6	93.600
2007 e		9	374.4	93.6	93.600
2008 e		9	374.4	93.6	93.600
2009 e		9	374.4	93.6	93.600
2010 e		9	374.4	93.6	93.600
2011 e		9	374.4	93.6	93.600
2012 e		9	374.4	93.6	93.600
2013 e		9	374.4	93.6	93.600
2014 e		7	291.2	72.8	72.800
2015 e		5	208.0	52.0	52.000
2016 e		4	166.4	41.6	41.600
2017 e		0	0	0	0
IRR		80%			
NPV @7%		$387 million			

Table C3. Cash Flow From Improved Food Processing Yield, Optimal Scenario

Year	*ATP investment (million $)*	*Volume processed meat (million pounds)*	*2 percent yield loss reduction (million pounds)*	*Value avoided yield loss (million $)*	*Additional cost (c/lb)*	*Incremental cost (million $)*	*Cash flow (million $)*
1996	–0.861						–0.861
1997	–0.915						–0.915
1998	–0.602						–0.602
1999	0						0
2000	0						0
2001 e	0						0
2002 e		0	0	0	1	0	0
2003 e		83.2	1.664	8.736	1	0.83	7.904
2004 e		166.4	3.328	17.472	1	1.66	15.808
2005 e		208.0	4.160	21.840	1	2.08	19.760
2006 e		374.4	7.488	39.312	1	3.74	35.568
2007 e		374.4	7.488	39.312	1	3.74	35.568
2008 e		374.4	7.488	39.312	1	3.74	35.568
2009 e		374.4	7.488	39.312	1	3.74	35.568
2010 e		374.4	7.488	39.312	1	3.74	35.568
2011 e		374.4	7.488	39.312	1	3.74	35.568
2012 e		374.4	7.488	39.312	1	3.74	35.568
2013 e		374.4	7.488	39.312	1	3.74	35.568
2014 e		291.2	5.824	30.576	1	2.91	27.664
2015 e		208.0	4.160	21.840	1	2.08	19.760
2016 e		166.4	3.328	17.472	1	1.66	15.808
2017 e		0	0	0	1	0	0
IRR		61%					
NPV @7%	$146 million						

Table C4. Cash Flow From Food Processing Throughput, Optimal Scenario

Year	*ATP investment (million $)*	*Volume processed meat (million pounds)*	*Increased volume by 1 percent (million pounds)*	*Cash flow (million $)*
1996	–0.861			–0.8610
1997	–0.915			–0.9150
1998	–0.602			–0.6020
1999	0			0
2000	0			0
2001 e	0			0
2002 e		0	0	0
2003 e		83.2	0.832	0.4368
2004 e		166.4	1.664	0.8736
2005 e		208.0	2.080	1.0920
2006 e		374.4	3.744	1.9656
2007 e		374.4	3.744	1.9656
2008 e		374.4	3.744	1.9656
2009 e		374.4	3.744	1.9656
2010 e		374.4	3.744	1.9656
2011 e		374.4	3.744	1.9656
2012 e		374.4	3.744	1.9656
2013 e		374.4	3.744	1.9656
2014 e		291.2	2.912	1.5288
2015 e		208.0	2.080	1.0920
2016 e		166.4	1.664	0.8736
2017 e		0	0	0
IRR	20%			
NPV @7%	$6 million			

Table C5. Cash Flow From Replacing Cryogenic Systems, Optimal Scenario

Year	*Cumulative cryogenic units replaced (unit)*	*Volume processed meat (million pounds)*	*Avoided cost (c/lb)*	*Cash flow (million $)*
1996				–0.861
1997				–0.915
1998				–0.602
1999				0
2000				0
2001 e				0
2002 e	1	41.6	–2	0.832
2003 e	3	124.8	–2	2.496
2004 e	6	249.6	–2	4.992
2005 e	10	416.0	–2	8.320
2006 e	12	499.2	–2	9.984
2007 e	12	499.2	–2	9.984
2008 e	12	499.2	–2	9.984
2009 e	12	499.2	–2	9.984
2010 e	12	499.2	–2	9.984
2011 e	12	499.2	–2	9.984
2012 e	12	499.2	–2	9.984
2013 e	11	457.6	–2	9.152
2014 e	9	374.4	–2	7.488
2015 e	6	249.6	–2	4.992
2016 e	2	83.2	–2	1.664
2017 e	0	0	–2	0
IRR	43%			
NPV @ 7%	$41 million			

Table C6. Combined Cash Flow, Optimal Scenario

A Year	B Cash flow from quality (million $)	C Cash flow from yield loss (million $)	D Cash flow from throughput (million $)	E Cash flow from cryo replacement (million $)	F Cash flow B+C+D+E (million $)
1996					–0.8610
1997					–0.9150
1998					–0.6020
1999					0
2000					0
2001 e					0
2002 e	0	0	0	0.832	0.8320
2003 e	20.8	7.904	0.4368	2.496	31.6368
2004 e	41.6	15.808	0.8736	4.992	63.2736
2005 e	52.0	19.760	1.0920	8.320	81.1720
2006 e	93.6	35.568	1.9656	9.984	141.1176
2007 e	93.6	35.568	1.9656	9.984	141.1176
2008 e	93.6	35.568	1.9656	9.984	141.1176
2009 e	93.6	35.568	1.9656	9.984	141.1176
2010 e	93.6	35.568	1.9656	9.984	141.1176
2011 e	93.6	35.568	1.9656	9.984	141.1176
2012 e	93.6	35.568	1.9656	9.984	141.1176
2013 e	93.6	35.568	1.9656	9.152	140.2856
2014 e	72.8	27.664	1.5288	7.488	109.4808
2015 e	52.0	19.760	1.0920	4.992	77.8440
2016 e	41.6	15.808	0.8736	1.664	59.9456
2017 e	0	0	0	0	0
IRR		90%			
NPV @ 7%	$585	million			
PV Investment	($2.10)	million			
PV of Cash Flow	$587	million			
Benefit:Cost		280 :1			

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ABOUT THE AUTHOR

Dr. Thomas Pelsoci is the managing director of Delta Research Co., specializing in the economic assessment of new technologies and manufacturing processes, including prospective economic impact studies during the early stage proof of concept and demonstration phases. His industrial experience includes positions as R&D engineer at TRW and as management consultant in the high technology practice of KPMG Peat Marwick. Subsequently, Dr. Pelsoci held senior banking positions at First National Bank of Chicago and at Sanwa Bank, specializing in financing information systems and technology projects. He received a degree in Mechanical Engineering from Case Western Reserve University and a Ph.D. in Public Policy and Administration from the University of Minnesota.