



Development of Refrigeration and Air-Conditioning Technologies for
Practical Use of Next-Generation Low-GWP Refrigerants

Volume 1

Project Overview

FY2023-2025 Progress Report

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New Energy and Industrial Technology Development Organization (NEDO)

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1. Background and Policy Significance

1.1 Background

This project is based on the recognition that refrigerant transition is not merely an "environmental issue" but rather a matter of industrial strategy. Hydrofluorocarbon (HFC) refrigerants have been widely adopted in refrigeration and air-conditioning as substitutes for CFC and HCFC refrigerants because their ozone depletion potential (ODP) is zero. However, HFCs have a high global warming potential (GWP) and exert a substantial impact as greenhouse gases. Thus, reducing the use of HFC refrigerants and shifting to refrigerants with lower GWP has become a critical issue in the refrigeration and air-conditioning sector.

The Kigali Amendment to the Montreal Protocol as adopted in 2016 requires developed countries to reduce their production and consumption of HFCs by 85 % by 2036 relative to the average level in 2011–2013. In Japan as well, through the operation of the designated-product system under the Act on Rational Use and Proper Management of Fluorocarbons and the Ozone Layer Protection Act, efforts are being made to lower the GWP of refrigerants and to phase down the use of HFCs. Furthermore, suppressing HFC emissions is considered increasingly critical as an important step toward the realization of carbon neutrality by 2050. Fig. 1.1-1 compares the supply-and-demand cap values for HFC refrigerants under Japan's implementation of the Kigali Amendment as reported by the Ministry of Economy, Trade and Industry with the allocated quantities for HFCs under the Ozone Layer Protection Act (through 2025) and the projected future demand for HFCs (from 2025 onward). The projections indicate that the cap values under the Kigali Amendment for 2029 and 2034 can barely be met. However, doing so on the premise of reserving approximately 10% of the Kigali Amendment baseline would require that all target values for designated products be fully achieved, that substitution by low-GWP refrigerants currently under development in projects managed by the New Energy and Industrial Technology Development Organization (NEDO) and similar initiatives proceed, and that measures to prevent atmospheric release and promote recovery be thoroughly implemented from the perspective of effective resource utilization while reclaimed refrigerants are utilized to the maximum extent possible.

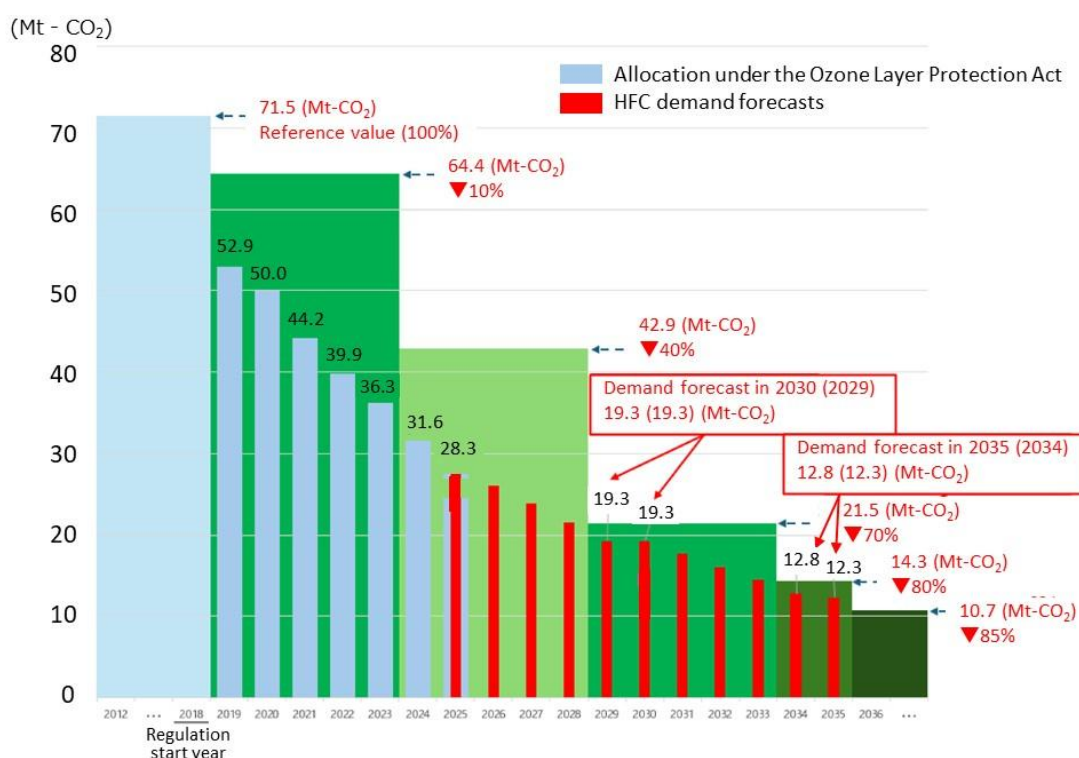


Figure 1.1-1 Comparison of regulatory limits based on the Kigali Amendment and HFC demand forecasts

In Japan, HFCs account for more than 90 % of greenhouse gas emissions other than CO₂. Figure 1.1-2 shows emission trends for the four major fluorinated greenhouse gases in Japan, including HFCs, perfluorocarbons (PFCs), sulfur

hexafluoride (SF₆), and nitrogen trifluoride (NF₃). In recent years, emissions of PFCs, SF₆, and NF₃ have declined substantially, whereas those of HFCs remain persistently high. Approximately 83 % of HFC emissions originate from refrigeration and air-conditioning equipment, yet only about 13 % of the refrigerants charged into these systems are recovered after use. Given the difficulty of recovery and recycling, reducing the GWP of the working fluid is an important mitigation measure. However, candidate next-generation refrigerants face some major technical challenges in achieving performance equivalent to that of existing HFC-based systems, and their deployment is often hindered by flammability and chemical instability. Equipment used in the refrigeration and air-conditioning sector tends to have a particularly long service life, and a given unit can become a source of emissions for more than a decade once it is placed on the market. Refrigerant choices made at the present time will accordingly have a major influence on medium- to long-term greenhouse gas emissions. Therefore, the early transition from HFC refrigerants to next-generation low-GWP refrigerants is an important policy issue that involves compliance with international treaties and the operation of domestic regulatory systems in addition to the associated technical concerns.

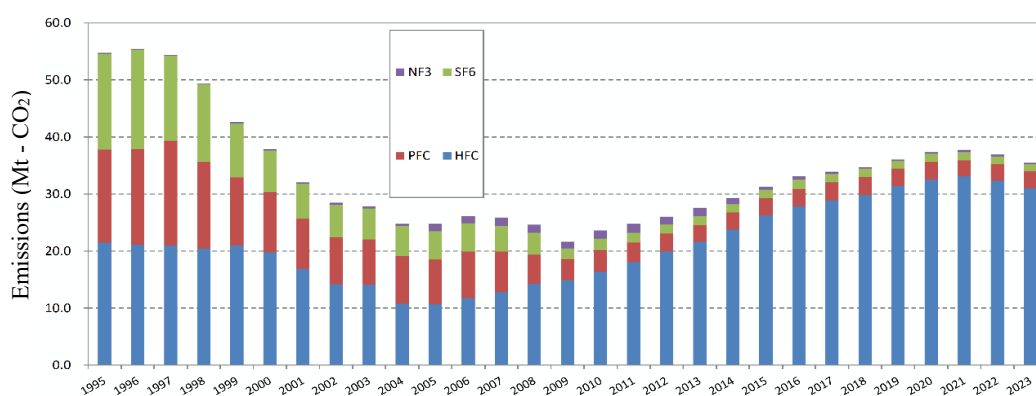


Figure 1.1-2 Annual emissions of four greenhouse gases (HFC, PFC, SF₆, NF₃) in Japan

1.2 Options and challenges surrounding refrigerant transition

Two broad options may be considered in undertaking a transition in refrigerants to reduce HFCs, including an approach centered on natural refrigerants and an alternative strategy centered on HFO-based refrigerants. Although natural refrigerants generally exhibit extremely low GWP, depending on the application they also present challenges such as high flammability, toxicity, corrosiveness, elevated operating pressure, and reduced efficiency. Accordingly, they cannot be directly applied to all uses of refrigeration and air-conditioning equipment. For example, although propane is regarded as a promising low-GWP refrigerant, it is understood to face major constraints in practical applications because it is highly flammable.

In contrast, new HFO-based refrigerants such as HFO-1123 and R-1132(E) are being developed by Japanese refrigerant manufacturers as candidates for broader applications because they can exhibit extremely low GWP. If these refrigerants are designed appropriately as mixtures, they can support design goals of reducing GWP while achieving better performance while maintaining continuity with existing refrigeration and air-conditioning equipment technologies. In this project, practical implementation of refrigerant mixtures centered on such domestically developed HFO-based refrigerants is regarded as an important direction for further research.

However, this option involves some clear technical hurdles. First, HFO-1123 and R-1132(E) may undergo self-decomposition reactions in conditions with high temperature and pressure, which substantially hinders their practical application in terms of safety. Second, in HFO-based refrigerant mixtures, temperature glide and differences in thermophysical properties can reduce the performance of heat pump machinery relative to that of current HFC refrigerant equipment. Therefore, low GWP alone is not sufficient for practical applications given that candidate solutions must suppress self-decomposition reactions and simultaneously improve heat-pump performance.

1.3 Policy significance of this project

This project seeks to provide Japan with a realistic and strategic technological response to international demands for HFC reduction, including those under the Kigali Amendment to the Montreal Protocol. In the refrigeration and air-conditioning sector, the basic plan clearly indicates that future reduction targets will be difficult to achieve if existing HFC refrigerants continue to be used. Under such constraints, this project seeks to accelerate the transition to next-generation refrigerants by pursuing a wide variety of endeavors from the exploration of candidate low-GWP refrigerant

mixtures to the development and evaluation of applicable equipment. Residential air conditioners and related systems are the primary targets of interest in this project.

Furthermore, the project aims to maintain and strengthen the international competitiveness of Japan's domestic refrigerant industry and refrigeration and air-conditioning industry in addition to facilitating regulatory compliance. The accumulated strengths of domestic industrial concerns in the development of refrigerants, equipment design, and related technologies might not be fully utilized if the refrigerant transition were to proceed toward complete dependence on natural refrigerants, especially propane. This accordingly weakens their competitive advantages in the international market. By contrast, the adoption of domestically developed HFO-based refrigerant mixtures in practical applications would make it possible to capitalize on the technological accumulation of domestic refrigerant manufacturers while also establishing new low-GWP equipment technologies in collaboration with equipment manufacturers. Thus, the basic plan defines providing some contribution to the expansion of Japanese companies' share in the global market as an intended outcome of this project.

Moreover, the project conducts integrated research and development encompassing refrigerants, safety, equipment, and system evaluations rather than pursuing the development of new materials or equipment independently. The practical implementation of domestically developed HFO-based refrigerants requires the preparation of thermophysical property data, the establishment of safety evaluation methods, the development of component technologies such as heat exchangers and compressors as well as evaluation methods for the overall system, including life cycle climate performance (LCCP). By advancing these elements not through isolated optimization but through their interrelationships, this project aims to construct a technological system that is genuinely implementable in practice.

1.4 Characteristics of this project

The characteristics of this project are summarized as follows.

First, this project is intended to be responsive to policy and undertake strategic research and development to address which technological route Japan should select and how that route should be connected to social implementation in response to the demands for refrigerant transition imposed by international treaties and domestic regulatory systems. In contrast, exploring entirely new research themes is not an objective.

Second, a perspective focused on industrial policy is adopted to maintain and strengthen the competitiveness of domestic industry through the practical implementation of domestically developed HFO-based refrigerant mixtures. This is contrasted with a simple, comprehensive transition to natural refrigerants, which is expected to involve some notable drawbacks as discussed above.

Third, the project is pursued in an integrated fashion to address the two essential challenges posed by domestically developed HFO-based refrigerants directly. These include the self-decomposition reaction, which constitutes their greatest disadvantage, and the decline in heat-pump performance when refrigerant mixtures are applied. It also aims to advance industrial processes in an integrated manner from the development of new refrigerants to the design and evaluation of equipment.

Thus, this project is of particular significance because international regulatory compliance is addressed in an integrated and coherent manner alongside domestic industrial strategy and the resolution of technological challenges.

2. Basic Plan Overview

This is a national project launched by NEDO in fiscal year 2023 to realize the practical application of low-GWP refrigerants and establish compatible refrigeration and air-conditioning equipment technologies.

While premised on responding to the HFC reduction obligations under the Kigali Amendment to the Montreal Protocol, this project aims to advance the practical implementation of low-GWP refrigerants and equipment by leveraging the technological foundations of domestic refrigerant and equipment manufacturers. A key characteristic of the project is that it promotes activities ranging from the exploration of refrigerant candidates to the establishment of equipment-application technologies and the development of evaluation methodologies in an integrated manner.

2.1 Basic project information

The basic framework of this project is summarized as follows.

- Project period: five years, from FY2023 to FY2027
- Implementing organization: NEDO (Circular Economy Department)
- Target field: the refrigeration and air-conditioning sector, with a focus on residential air conditioners
- Implementation format: a combination of commissioned projects and subsidized projects

This project is intended to shorten the development period required for new technologies, which generally takes approximately ten years from the development of a new refrigerant to practical applications with manufactured equipment. It also aims to achieve early practical implementation in response to international regulatory trends.

Figure 2.1-1 illustrates the development status of next-generation refrigerants. The horizontal axis indicates the temperature range of the equipment, and the vertical axis indicates the capacity level of the equipment. For the equipment shown in green, low-GWP refrigerants have already become widespread. For refrigerated warehouses and medium-scale commercial refrigeration equipment shown in light blue, refrigerants such as HFO refrigerants and carbon dioxide have been developed, and efforts to reduce GWP are being advanced through the designated-product system under the Act on Rational Use and Proper Management of Fluorocarbons to promote wider adoption. R-32 is currently used for the air conditioners and small commercial refrigeration equipment shown in brown. However, further reductions in GWP are required. Highly flammable hydrocarbons have been identified as candidate next-generation refrigerants for these fields. Therefore, the question of whether they can be used safely must be considered.

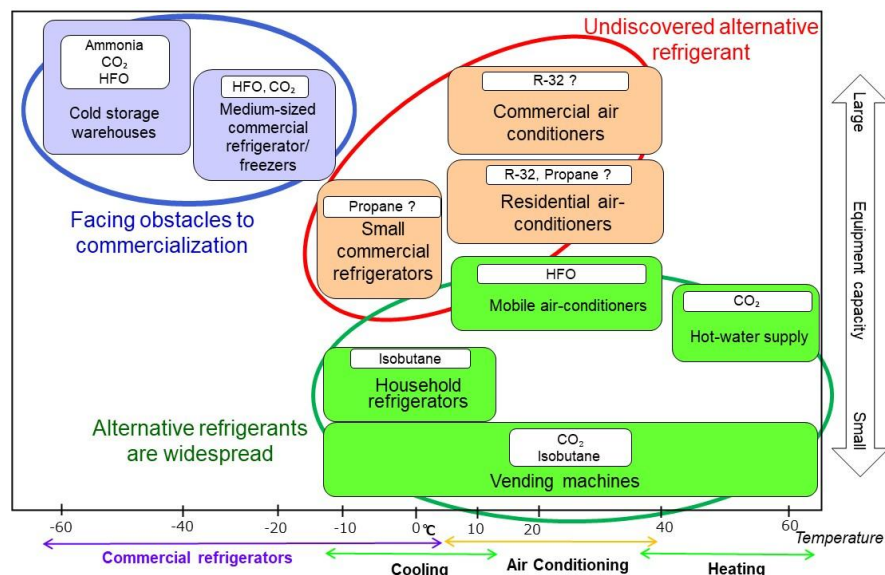


Figure 2.1-1 Development status of low-GWP refrigerant by application

2.2 Basic policy for research and development

In this project, the elements required for the practical application of low-GWP refrigerants are not treated separately. Rather, research and development is advanced in an integrated manner based on the following perspectives.

First, the project aims to establish technologies that simultaneously satisfy the three requirements of environmental performance, safety, and performance. Lowering GWP alone does not suffice for practical implementation; comprehensive technological feasibility, including safety and equipment performance, is required.

Second, the project aims to conduct integrated technology development that includes equipment component technologies such as heat exchangers and compressors as well as evaluations of entire systems rather than simply developing new refrigerants. Through this approach, performance issues specific to refrigerant mixtures are to be addressed in combination with equipment-side technologies.

Third, the project develops common foundational technologies such as thermophysical property data, safety-evaluation methods, and LCCP evaluation to enable international standardization and utilization in industry.

Thus, this project pursues research and development oriented towards practical implementations based on the integrated optimization of refrigerants, equipment, and evaluation.

2.3 Division of roles between commissioned and subsidized projects

This project is structured to combine commissioned and subsidized projects.

Foundational technologies such as refrigerant properties, safety evaluation, and system evaluation are developed in the commissioned projects, and knowledge that can be shared across the entire industry is accumulated. In the subsidized projects, by contrast, companies utilize the results and take the lead in developing and commercializing real equipment for practical applications.

Thus, the project adopts the following clear division of roles.

- Commissioned projects: develop foundational technologies (collaborative domain)
- Subsidized projects: develop commercial products (competitive domain)

Through this clear division of roles, the project seeks to achieve efficient research and development and to accelerate practical implementation. In this project, the subsidized projects are limited in scale, and the commissioned projects serve as the core of the project as a whole.

2.4 Structure of the research and development items

This project broadly consists of two key research and development items.

2.4.1 Development and evaluation of low-GWP refrigerant mixtures (commissioned project)

Under this item, universities and public research institutions primarily conduct the exploration and evaluation of candidate low-GWP refrigerant mixtures.

Specifically, the project carries out the following.

- Selection of candidate refrigerant mixtures
- Measurement of thermophysical properties and formulation of equations of state
- Safety evaluation concerning flammability and self-decomposition reactions
- Evaluation of refrigeration-cycle characteristics and performance
- Evaluation of life-cycle impacts (LCCP)

Through these efforts, the project develops an evaluation foundation ranging from the fundamental properties of refrigerants to system performance.

This item serves to establish common foundational technologies (a collaborative domain) that do not depend on any individual company.

2.4.2 Development of equipment compatible with low-GWP refrigerants (subsidized project)

Under this item, companies primarily take the lead in developing refrigeration and air-conditioning equipment compatible with low-GWP refrigerants.

Specifically, the project carries out the following.

- Design of compressors and heat exchangers compatible with refrigerant mixtures
- Optimization of refrigeration cycles
- Performance evaluation and reliability assessment of actual equipment
- Operational verification under actual environmental conditions

Through these efforts, the project aims to establish equipment technologies for practical implementation.

This item constitutes research and development in a competitive domain premised on commercialization by companies.

2.5 Key goals of the project

This project builds on previous research and development conducted at NEDO (multiple projects since FY2011). Based on those achievements, the project aims to accelerate technology development toward practical implementations.

In previous projects, studies advanced the basic characteristics of low-GWP refrigerants and their applicability to equipment. This project goes one step further by pursuing the following goals.

- Presentation of candidate refrigerants for which implementation is expected to be practical
- Establishment of methods to evaluate their safety in practical applications
- Development of design guidelines for equipment

These goals are a defining feature of the project.

Accordingly, this project is considered critical in bridging the gap between basic research and practical implementations.

3. Research and Development Objectives and Outcomes

3.1 Objectives of research and development

This project aims to realize the practical implementation of low-GWP refrigerants and to establish refrigeration and air-conditioning equipment technologies compatible with such refrigerants on the premise of responding to obligations to reduce HFCs under the Kigali Amendment to the Montreal Protocol.

In particular, this project is focused on the practical implementation of domestically developed HFO-based refrigerant mixtures based on HFO-1123 and R-1132(E) that are being developed by Japanese refrigerant manufacturers. This approach is important in terms of pursuing lower GWP and better equipment performance while maintaining and advancing the technological foundations of domestic industry.

However, these refrigerants have not yet reached practical implementation and involve the following essential challenges.

- Potential occurrence of self-decomposition reactions under high-temperature and high-pressure conditions
- Decline in heat-pump performance caused by the temperature glide specific to refrigerant mixtures
- Insufficiently developed basic thermophysical properties for HFO-based refrigerant mixtures

Accordingly, the objective of this project is to overcome these challenges and establish new refrigerants and associated equipment and technology as systems designed to satisfy the requirements of practical applications in terms of safety, performance, and environmental compatibility.

3.2 Principal technical challenges

The research and development challenges in this project may be broadly divided into the following four categories.

3.2.1 Establishment of the basic thermophysical properties of HFO-based refrigerant mixtures

For the basic thermophysical properties of HFO refrigerant mixtures, the following steps are required.

- Measurement of the basic thermophysical properties of promising HFO refrigerant mixtures
- Development of equations of state based on those properties
- Contribution to international database development so that the data can be used in NIST REFPROP

3.2.2 Elucidation and suppression of self-decomposition reactions

The self-decomposition reactions specific to HFO-based refrigerants may occur owing to the conditions of high temperature and pressure inside compressors as well as to electrical factors. These reactions constitute one of the greatest barriers to practical implementation. Accordingly, the project must address the following points.

- Identification of the conditions under which the reaction occurs
- Elucidation of the mechanism of such reactions
- Establishment of safety evaluation methods to promote international standardization concerning safety

Through these efforts, the conditions under which safe use is possible must be clarified.

3.2.3 Securing and improving heat-pump performance

HFO-based refrigerant mixtures may exhibit lower performance than conventional HFC refrigerants because of temperature glide and differences in thermophysical properties. Accordingly, the project must address the following concerns.

- Improvement of the heat-transfer characteristics of heat exchangers
- Compatible design of compressors
- Optimization of refrigeration cycles

Through these efforts, the project aims to achieve performance equivalent to or better than that of current equipment.

3.2.4 Establishment of evaluation methods and design foundations

Rigorous evaluations based on a technical foundation that integrates property data, safety evaluation, and environmental impact assessment are indispensable in the practical implementation of new refrigerants. Accordingly, the project must address the following.

- Development of equations of state and thermophysical property data
- Establishment of methods to evaluate the safety of practical applications
- Advancement of methods to evaluate an entire system, including LCCP evaluation

3.3 Outputs (research and development results)

The principal outputs to be generated by this project are described as follows.

First, the project will select promising low-GWP refrigerant mixture candidates and identify their characteristics systematically. This will provide a foundation to select refrigerants for practical applications.

Second, the project will construct thermophysical property data and equations of state for refrigerants to enable performance prediction with high accuracy and support the design of new equipment.

Third, the project will establish methods to evaluate the safety of these technologies, including those for self-decomposition reactions. This is expected to constitute an important achievement with a view to international standards.

Fourth, the project will formulate design guidelines for heat exchangers and compressors to provide a foundation for equipment design compatible with refrigerant mixtures.

Fifth, the project will establish methods to evaluate the performance and LCCP of refrigeration and air-conditioning systems to address the selection of refrigerants, the design of new equipment, and environmental impact assessment in an integrated manner.

These outputs will serve as common foundational technologies shared across the industry as a whole in addition to supporting product development by individual companies.

3.4 Outcomes (social and industrial effects)

The expected outcomes of this project can be organized by their respective time horizons as follows.

3.4.1 Short-term outcomes (During the project period to immediately after completion)

- Clarification of refrigerant candidates for practical implementation
- Establishment of the foundational technologies required for equipment design
- Preparation of technical data for safety evaluation and standardization

3.4.2 Medium-term outcomes (Around 2030)

- Commercialization and market introduction of equipment compatible with low-GWP refrigerants
- Diffusion of products compliant with institutional systems such as the Act on Rational Use and Proper Management of Fluorocarbons
- Progress in reducing greenhouse gas emissions in the refrigeration and air-conditioning sector

3.4.3 Long-term outcomes (2036 and beyond)

- Contribution to the achievement of the HFC reduction targets under the Kigali Amendment
- Contribution to the realization of carbon neutrality by 2050
- Strengthening of international competitiveness in the field of low-GWP refrigerants and related equipment

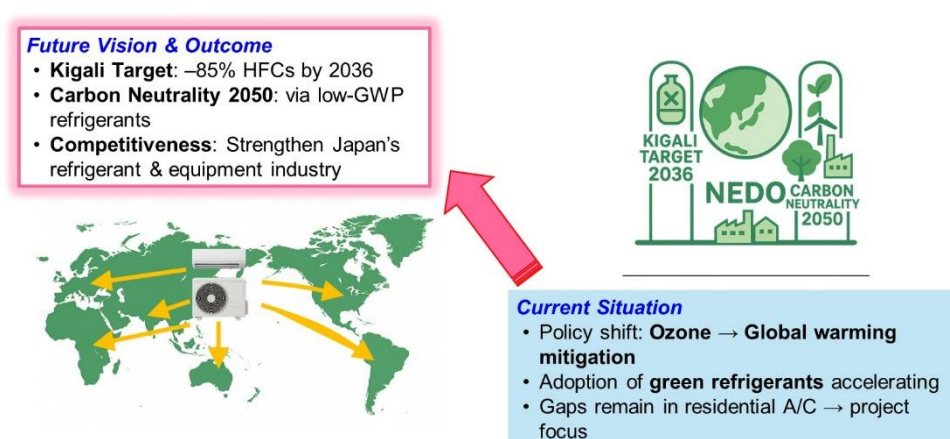


Figure 3.4-1 Desired future vision and outcomes

3.5 Path from outputs to outcomes

In this project, the process from understanding the properties of new refrigerants to the design of new equipment, the evaluation of new systems, and their practical implementation will be advanced in stages to ensure that research and development results are connected to social implementation. Figure 3.5-1 shows the pathway from the research and development outputs of this project to the resulting outcomes. It is assumed that equipment using the new refrigerants developed in this project will begin to spread widely in the market from around 2030 onward.

In particular, key aspects include

- understanding of refrigerant properties and safety,

- securing equipment performance, and
- comprehensive evaluation at the system level.

By achieving these elements in an integrated manner, the project will establish a technological system that can be implemented in practical applications.

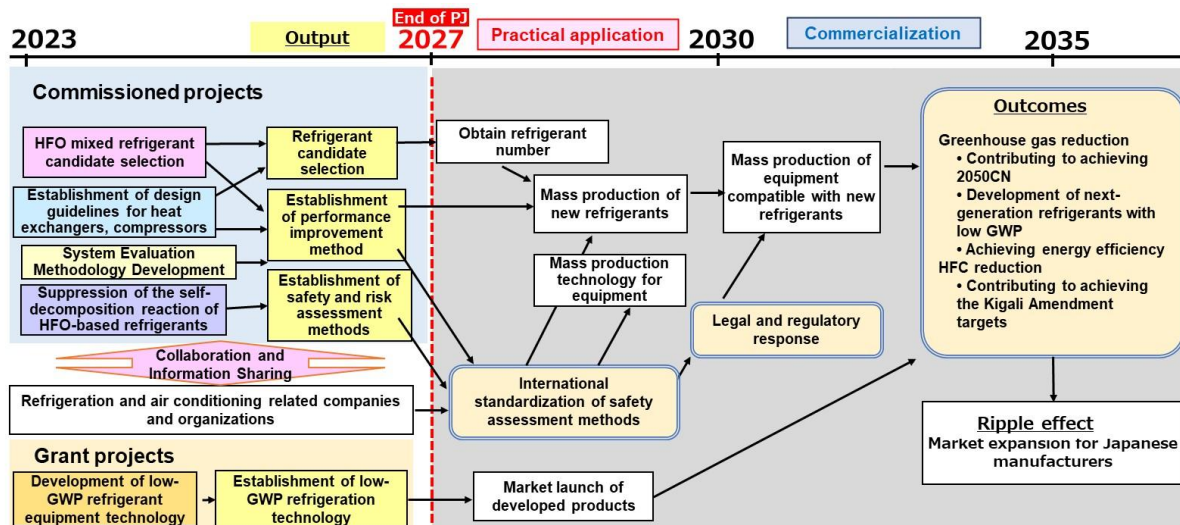


Figure 3.5-1 Path from research output to outcome achievement

4. Research and Development Structure

To address the complex challenges required for the practical implementation of low-GWP refrigerants, this project is being carried out under NEDO through collaboration among universities, public research institutions, and companies. Under the overall supervision of the project manager, the project and subproject leaders are responsible for promoting the research and development activities.

4.1 Basic structure of the project framework

This project adopts a two-layer structure combining commissioned projects (basic research) and subsidized projects (practical implementation development).

- Commissioned projects focus on establishing foundational technologies concerning refrigerants, safety, equipment, and evaluation.
- Subsidized projects promote the development of equipment and practical implementation by companies.

This structure makes it possible to connect research and development results to practical implementation in a staged manner.

4.2 Composition of the research groups in the commissioned projects

In the commissioned projects, the following four research groups have been established according to their respective technological fields. Figure 4.2-1 presents the organizational structure of the project, and Table 4.2-1 presents excerpts of the research content of each group.

4.2.1 Group for refrigerant property evaluation

The Group for Refrigerant Property Evaluation, consisting of Kyushu University, Kyushu Sangyo University, Nagasaki University, the National Institute of Advanced Industrial Science and Technology (AIST), and Aizoth Co., Ltd., measures the thermophysical properties of candidate refrigerants, formulates equations of state, and provides validated data for implementation in the NIST REFPROP database. In addition to measuring flammability limits and burning velocities, the group also studies mixing rules that describe the behavior of refrigerant mixtures. By evaluating environmental impacts over the entire life cycle, the group identifies and improves compositions that show promise as next-generation refrigerants.

4.2.2 Group for safety evaluation

The Group for Safety Evaluation, consisting of the Central Research Institute of Electric Power Industry, Suwa University of Science, AGC Inc., and Daikin Industries, Ltd., aims to incorporate methods to evaluate stability into international safety standards such as ISO 817. The group studies test procedures for self-decomposition reactions and conducts risk assessments for actual air-conditioning and refrigeration systems, including the possibility of dielectric discharge under compressor conditions with high temperature and pressure. These results contribute to the establishment of reliable safety standards for next-generation refrigerants. In cooperation with the Japan Refrigeration and Air Conditioning Industry Association, the group conducts risk assessments of HFO-based refrigerants in which self-decomposition reactions have been suppressed, and it plays a central role in addressing safety issues that determine the feasibility of practical implementation.

4.2.3 Group for equipment component technologies

The Group for Equipment Component Technologies consists of Saga University, Kobe University, Tokyo University of Marine Science and Technology, UACJ Corporation, Shizuoka University, Osaka Electro-Communication University, and Advance Composite Co., Ltd. This group works on technologies for suppressing heat-transfer deterioration caused by the temperature glide of refrigerant mixtures and on the development of high-performance heat exchangers. With respect to compressors, the group elucidates the dissolution behavior of refrigerants in compressors, advances the development of lightweight composite materials suitable for compressor components, and works toward higher compressor rotational speeds.

4.2.4 Group for system performance evaluation

The Group for System Performance Evaluation, consisting of Waseda University and The University of Electro-Communications, is developing a comprehensive simulation platform for predicting system performance using various low-GWP refrigerants. This simulator enables LCCP analysis of newly proposed refrigerant compositions and helps identify the most promising candidates for practical implementation. By advancing refrigeration-cycle performance analysis and system-evaluation methods, the group constructs an integrated evaluation foundation for refrigerants and equipment through simulation technology and LCCP evaluation.

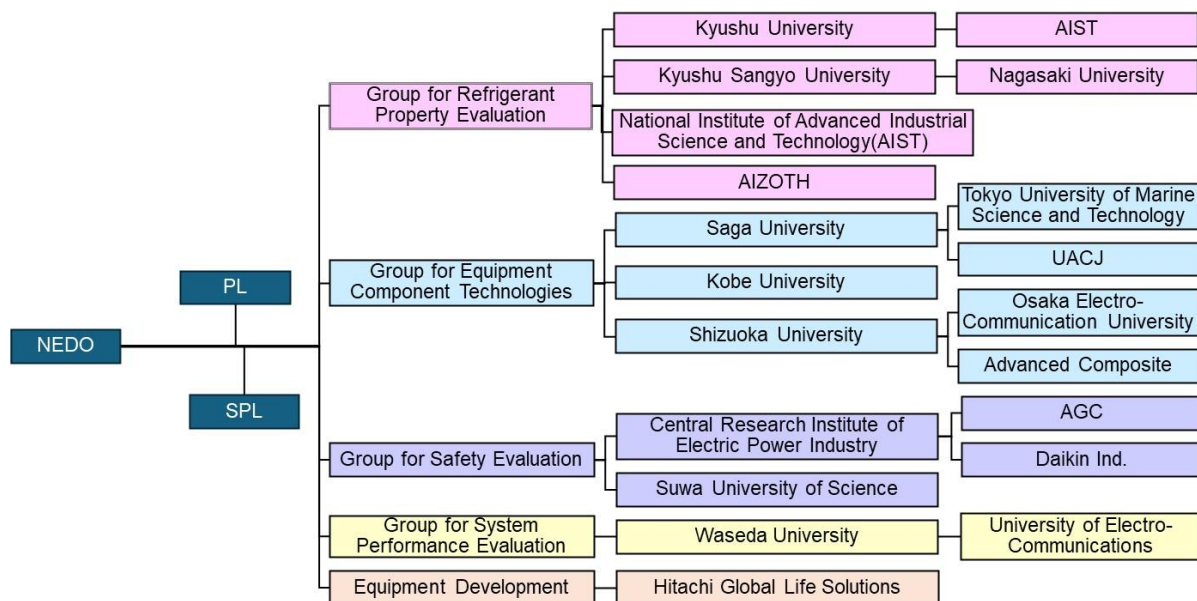


Figure 4.2-1 Project structure

Table 4.2-1 Project implementation themes and contents

Theme	Contents
■ Commissioned project (Development of low-GWP refrigerants suitable for residential air conditioning, etc.)	
Group for Refrigerant Property Evaluation	• Acquisition of thermophysical property data and narrowing down of candidate refrigerants • Developing equation of state and mixing model for use in NIST's REFPROP
Group for Equipment Component Technologies	• Regarding heat exchangers, development of technology to suppress heat transfer deterioration of mixed refrigerants and high-performance heat exchangers • Regarding compressors, clarifying the refrigerant dissolution behavior in compressors and developing lightweight composite materials suitable for compressor parts
Group for Safety Evaluation	• Development of evaluation method for HFO refrigerant self-decomposition reaction and low GWP refrigerant mixture composition
Group for System Performance Evaluation	• Development of system evaluation methods and AI optimization algorithms for refrigeration cycle simulators
■ Subsidized project (Development of equipment using low-GWP refrigerants)	
Equipment Development	• Development of a condensing unit using low-GWP refrigerants

4.3 Subsidized projects

In the subsidized projects, companies take the lead in developing equipment compatible with low-GWP refrigerants and in verifying performance.

Although the scale of the subsidized projects in this project is limited, they do play the following important roles.

- Application of the foundational technologies obtained in the commissioned projects to actual equipment
- Verification of performance and reliability toward practical implementation

They therefore serve an important function in connecting research and development results to social implementation.

4.4 Correspondence between technical challenges and the project structure

Figure 4.4-1 is a conceptual diagram that shows the relationship between system performance and mixture composition for R-1132(E)-based refrigerants. The qualitative trends shown in the figure are derived from thermodynamic performance calculations, particularly the dependence of the coefficient of performance (COP) on refrigerant composition and temperature-glide effects. The horizontal axis represents the mixing ratio of R-1234yf and R-1132(E). The COP of pure R-1234yf or pure R-1132(E) is approximately comparable to that of pure R-32. However, the mixing of R-1234yf and R-1132(E) causes a sharp decline in COP. This is attributable to the temperature glide of the refrigerant mixtures.

Because COP has been found to improve as the mixing ratio of R-1132(E) increases, it is expected based on the research of the Group for Safety Evaluation that the composition of R-1132(E) can be increased within a range in which there is no risk of self-decomposition reactions. Although performance can be partially recovered by mixing R-32, the overall efficiency remains lower than that of pure R-32. There is a limit to how large the mixing ratio of R-32 can be because mixing R-32 increases GWP.

To achieve system performance equivalent to that of current R-32-based refrigeration and air-conditioning equipment, technological improvements in components are required, especially heat exchangers and compressors. In the Group for Equipment Component Technologies, the development of heat exchangers is expected to improve the heat-transfer performance of refrigerants with large temperature glide. Of note, R-1234yf involves a known disadvantage in terms of its large specific vapor volume. Because the specific vapor volume of R-1234yf/R-1132(E) refrigerant mixtures is larger than that of R-32, they have the disadvantage of lower volumetric capacity. One countermeasure is to enlarge the compressor. However, in this project, higher compressor speed is being considered through weight reduction of the compressor's moving parts.

As shown in Figure 4.4-1, refrigerant composition, safety, and performance are in a trade-off relationship. This problem is difficult to solve through optimization in a single field alone. Thus, a cross-disciplinary research structure is indispensable in this project.

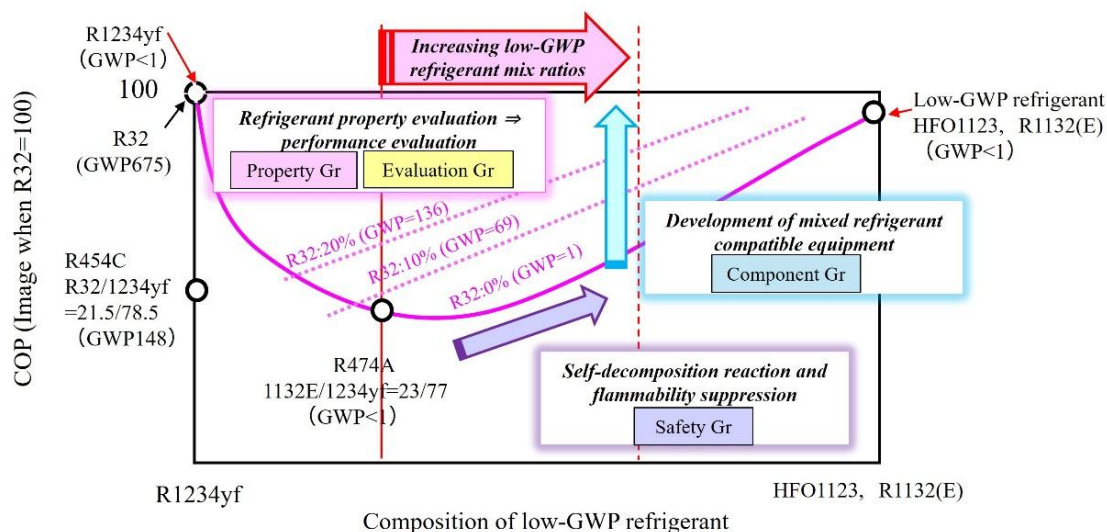


Figure 4.4-1 Conceptual relationship between refrigerant composition and system performance

4.5 Characteristics of cross-disciplinary collaboration

In this project, integrated optimization of refrigerants, equipment, and evaluation is pursued through the cyclical integration of the results generated by each research group.

For example,

- thermophysical property data from the Group for Refrigerant Property Evaluation are utilized in equipment design and system evaluation,
- knowledge from the Group for Safety Evaluation is reflected in the design and operating conditions specified for new equipment, and
- analysis results from the Group for System Performance Evaluation are fed back into the refrigerant selection and equipment design process.

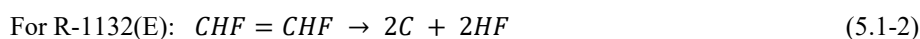
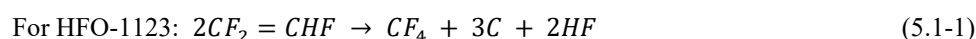
Through such cross-disciplinary collaboration, the project is able to respond in an integrated manner to challenges that are difficult to solve within a single technological field alone.

5. Examples of Project Research

5.1 Self-decomposition reactions of refrigerants being developed in NEDO

R-32 remains dominant as the primary refrigerant used in air-conditioning applications. For many years, there has been a demand for next-generation refrigerant candidates with low global warming potential and high safety. Accordingly, this project has focused on R-1132(E) and HFO-1123, which are obtained by substituting fluorine atoms for hydrogen atoms in ethylene. The properties of these substances are shown in Table 5.1-1. These compounds belong to the hydrofluoroolefin (HFO) family, which is characterized by carbon-carbon double bonds. However, such unsaturated fluorinated compounds have been shown to exhibit a tendency to undergo self-decomposition under high-temperature and high-pressure conditions. Thus, they have not yet been implemented in practical applications because of the potential safety risks.

As shown in Eqs. (5.1-1) and (5.1-2), the self-decomposition of these refrigerants can occur even in the absence of oxygen.



These reactions are strongly exothermic; they proceed even in the absence of oxygen and produce carbon and hydrogen fluoride as byproducts under conditions with high temperature and pressure.

Figure 5.1-1 presents a conceptual diagram of the self-decomposition pathways of HFOs. The figure shows two principal modes of self-decomposition: the disproportionation reaction occurring at intermediate temperatures and the pyrolytic decomposition reaction occurring under high-temperature or discharge conditions. The boundary line represents the transition from disproportionation to complete thermal decomposition. When a failure occurs inside the compressor, the HFO refrigerant may enter a high-temperature, high-pressure state that causes electrical short circuits or discharge and thereby induces self-decomposition. Under such conditions, the reaction temperature may exceed 1000 °C, leading to thermal decomposition.

Because this reaction is highly exothermic, ignition inside the compressor may accelerate flame propagation and lead to catastrophic failure such as the rupture of a casing. To suppress this phenomenon, the refrigerant must be mixed with inert or stabilizing components that absorb or neutralize reaction intermediates. Among the potential inhibitors examined, R-1234yf and R-32 have been identified as promising candidates provided that the resulting mixtures also satisfy these criteria.

Figure 5.1-2(a) shows a schematic pressure-temperature diagram showing the boundary conditions under which the self-decomposition reaction of R-1132(E) propagates. As temperature and pressure increase, the decomposition flame propagates more readily. Above the boundary line, the reaction becomes self-sustaining and poses a potential hazard, whereas below the boundary line propagation is suppressed and the refrigerant remains stable. Figure 5.1-2(b) shows in gray the typical operating pressure and temperature range encountered in refrigeration and air-conditioning systems. The stability boundary of pure R-1132(E) lies within this region. This suggests that self-decomposition may occur under certain conditions with high temperature and pressure during the operation of such equipment. When R-1234yf is added as a reaction inhibitor, the boundary shifts toward higher temperatures and pressures, which expands the safe operating range. If the stability boundary of the R-1132(E)/R-1234yf mixture lies completely outside the gray shaded region, the refrigerant may be regarded as thermally stable under normal system conditions.

Table 5.1-2 summarizes the thermophysical and environmental characteristics of internationally registered R-1132(E)-based mixtures. R-474 denotes a mixture of R-1132(E) and R-1234yf, whereas R-479 further contains R-32. The addition of R-32 improves system performance, but it also increases the GWP.

Table 5.1-1 Thermodynamic properties of low-GWP refrigerants

Refrigerant	HFO-1123	R-1132(E)
Formula	CHF=CF ₂	trans-CHF=CHF
Critical Temperature [°C]	58.6	75.7
Critical Pressure [MPa]	4.54	5.17
Boiling Point [°C]	-59.1	-52.6
Lower Flammability Limit [vol%]	6.3	4.4
Burning Velocity [cm·s ⁻¹]	6.5	30.5
Safety Class	-	A2

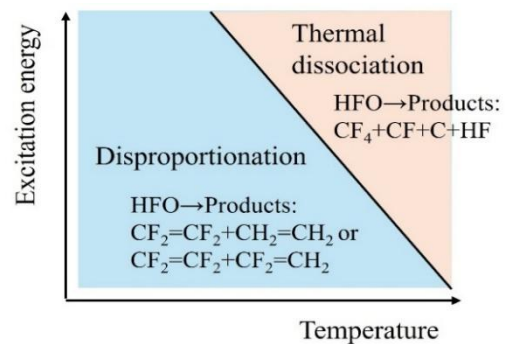


Fig. 5.1-1. Self-decomposition pathways of HFOs

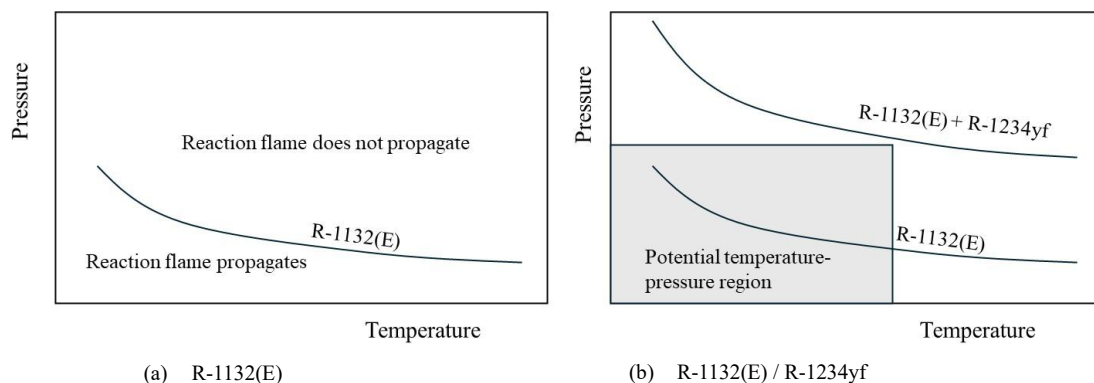


Figure 5.1-2. Propagation boundary of the self-decomposition flame for the R-1132(E)/R-1234yf mixture

Table 5.1-2. Thermophysical and environmental properties of R-1132(E) mixtures

Refrigerant		R-474A	R-474B	R-479A	R-479B
Composition	R-1132(E) [mass%]	23	31.5	28	23
	R-1234yf [mass%]	77	68.5	50.5	33
	R-32 [mass%]	-	-	21.5	44
Physical Property	Boiling Point [°C]	-43.4	-45.8	-50.5	-51.9
	Critical Temp. [°C]	87.8	85.2	80.5	78.1
	Critical Pres. [MPa]	4.05	4.22	4.81	5.23
GWP(AR4)		< 1	< 1	147	299
Safety Class		A2L	A2L	A2L	A2L

5.2 Basic performance of low-GWP refrigerant mixtures

Because non-azeotropic refrigerant mixtures exhibit temperature glide, cycle performance may decrease in comparison with that of pure refrigerants. Accordingly, some selected results of thermodynamic performance calculations using REFPROP Version 10 are presented below. The evaporator-side temperature glide of the R-32/1123/1234yf system is described before the results of the calculation for the refrigeration cycle are presented. Referring to Figure 5.2-1, the calculation is performed as follows.

- It is defined with reference to the evaporator outlet (dew-point temperature: T_d).
- The evaporation pressure is obtained from the dew-point temperature: P_e .
- The bubble-point temperature at the evaporation pressure is obtained: T_b .
- Temperature glide: $\Delta T_e = T_d - T_b$.

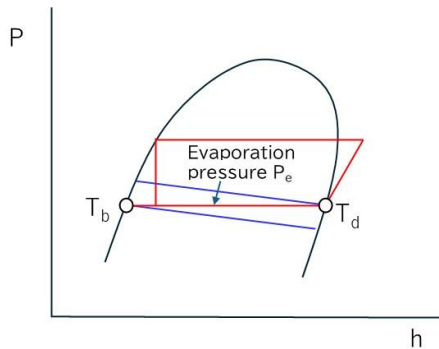


Figure 5.2-1 Definition of temperature glide

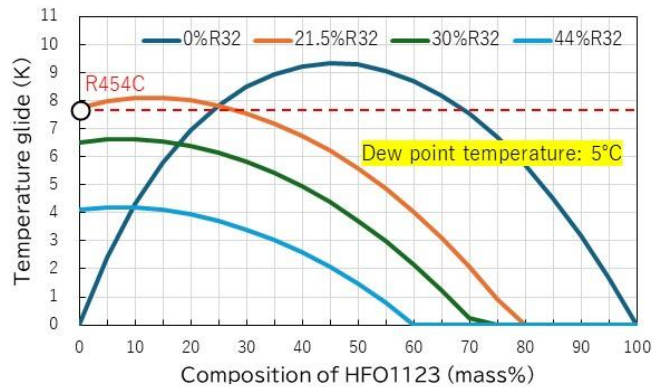


Figure 5.2-2 Temperature glide with a dew point of 5°C

Figure 5.2-2 shows the temperature glide of the R-32/1123/1234yf system when the dew-point temperature is 5 °C. The concentration of R-32 is taken as 0, 21.5, 30, and 44 mass%. The temperature glide of R454C is also shown for reference.

Next, the refrigeration-cycle performance is presented. The calculation conditions are as follows. The representative temperature of the evaporator is 5 °C, the pressure is constant, and the degree of superheating is 5 °C. The evaporator pressure is defined as $P_e = (1 - \alpha) P_b + \alpha P_d$, to consider the decline in the performance of the heat exchanger caused by temperature glide, where P_b and P_d respectively denote the bubble-point and dew-point pressure at 5 °C.

The representative temperature of the condenser is 40 °C, the pressure is constant, and the degree of subcooling is 5 °C. The condenser pressure is defined as $P_c = \beta P_b + (1 - \beta) P_d$. The isentropic efficiency of the compression process is given as 0.75.

When a value of $\alpha = \beta = 0.5$ is assumed, the decline in the performance of the heat exchanger due to temperature glide is neglected, whereas when $\alpha = \beta = 1$ is assumed, the maximum deterioration is represented. Figure 5.2-3 shows the cooling COP of the HFO-1123/1234yf/32 system under the assumption that $\alpha = \beta = 1$. Because GWP is determined by the concentration of R-32, the mass fraction of R-32 is fixed at 0, 20, 30, or 44 %. When R-32 is 0 %, the COP of the binary HFO-1123/1234yf mixture is substantially lower than the COP of the pure refrigerants. However, this decline is mitigated by adding R-32. Figure 5.2-4 shows the simulated improvement in the heat-exchanger performance of the HFO-1123/1234yf system when α and β are reduced from 1 to 0.5. Improvement in heat-exchanger performance may enhance the COP.

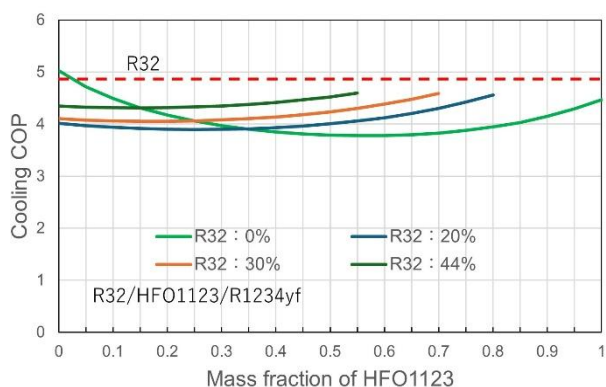


Figure 5.2-3. Cooling COP of R-32/HFO1123/1234yf mixture

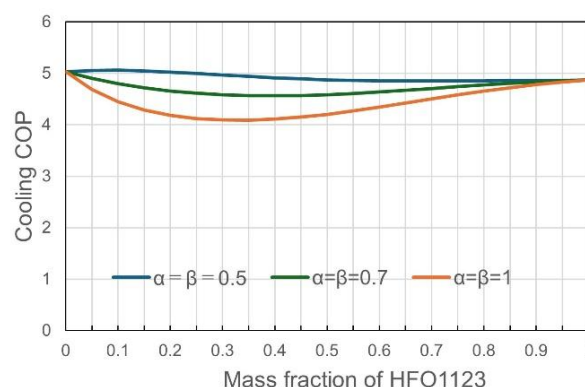


Figure 5.2-4 Effect of pressure on cooling COP of HFO-1123/1234yf mixture

6. Summary and Future Developments

This project has been promoted with the aim of realizing the practical implementation of low-GWP refrigerants and establishing refrigeration and air-conditioning equipment technologies compatible with such refrigerants to respond to obligations to reduce HFCs under the Kigali Amendment to the Montreal Protocol. In particular, the project seeks to reconcile environmental responsiveness with industrial competitiveness by focusing on the practical implementation of domestically developed HFO-based refrigerant mixtures rather than a simplistic transition to natural refrigerants.

Through the efforts undertaken to date, foundational technologies relating to refrigerant properties, safety, equipment component technologies, and system evaluation are being established in a staged manner, and the construction of a technological system for the practical implementation of low-GWP refrigerants is steadily progressing. In particular, research aimed at elucidating self-decomposition reactions and securing heat-pump performance is advancing. Moreover, the understanding of the principal issues that determine the feasibility of practical implementation is deepening.

This project has broad significance because it will concretely determine which technological route Japan should select in response to the policy demand for refrigerant transition and how that route should be connected to social implementation. In other words, this project will conduct and support research and development initiatives oriented towards practical implementations and promote the results in an integrated manner across regulatory compliance, technological development, and industrial strategy. Moreover, the project indicates the direction of future technological choices in the refrigeration and air-conditioning field.

During the project period, the optimization of candidate refrigerants must first be advanced, and methods to evaluate their safety must be established along with the preparation of design guidelines for the associated equipment. These developments will enhance the completeness of the technological foundation required for practical implementation. In particular, the systematization of knowledge concerning self-decomposition reactions and the establishment of safety design based on that are important prerequisites for international standardization and the introduction of new technologies to the market.

Furthermore, after the project is completed, it will be necessary to accelerate the introduction of equipment compatible with low-GWP refrigerants to the market while promoting product development and mass production by companies and ensuring consistency with standards and institutional systems. In this process, the property data, safety evaluation methods, and design guidelines developed in this project are expected to be utilized as the foundation for product development and international standardization.

Moreover, a successful refrigerant transition cannot be achieved by any single country alone, and consistency with international standardization and market trends is indispensable. Deploying the results obtained through this project within international frameworks and establishing technologies and evaluation methods originating in Japan as

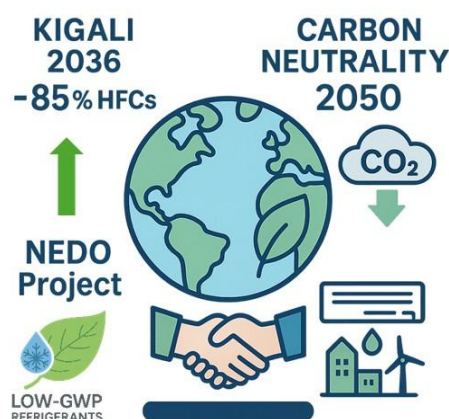


Figure 6.1-1 Outcomes of the project

international standards will be an important future issue. The following initiatives are planned from the perspectives of international outreach and human resource development to connect the results of this project reliably to social implementation.

- In fiscal year 2028, an international symposium will be held to disseminate the refrigerants and equipment technologies developed in this program broadly at an international level.
- In fiscal year 2029, after the completion of this program, a NEDO special lecture course is scheduled to be held for university affiliates, young engineers at equipment manufacturers, and similar participants to provide instruction on the refrigerants and equipment technologies developed in this program.

Ultimately, it is expected that the results of this project will contribute to the achievement of the HFC reduction targets under the Kigali Amendment and to the realization of carbon neutrality by 2050 while also strengthening Japan's international competitiveness in the field of low-GWP refrigerants and related equipment.