Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 54

Heat Pump Systems with Low-GWP Refrigerants

Country Report Japan

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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7.1 Executive Summary

The report provides an in-depth analysis of the life cycle climate performance (LCCP) and risk evaluations for heat pump systems using low-global warming potential (GWP) refrigerants in Japan. This study aims to identify suitable refrigerants, assess their environmental impact, and evaluate safety measures to mitigate associated risks. The LCCP evaluation adheres to guidelines from the International Institute of Refrigeration (IIR) and examines refrigerants such as R410A, R32, R454C, R290, and R22, chosen for their performance characteristics and potential as next-generation refrigerants.

Direct emissions are calculated based on refrigerant charge, annual leakage rate, and end-of-life emissions, while indirect emissions are derived from energy consumption over the equipment's operational life. The analysis employs the JRAIA standard model for air conditioners, simulating both cooling and heating conditions to determine annual energy consumption and the required refrigerant charge for each type. The risk assessments encompass multiple stages, including logistics, installation, usage, service, and disposal, analyzing scenarios to ascertain the probability of ignition and the presence of flammable spaces.

The findings reveal that risks during transportation and storage are minimal, provided appropriate safety measures are in place, keeping ignition probabilities below acceptable thresholds. During installation and service, risks are significantly reduced through professional training and the use of leak-detection devices. In the usage phase, implementing mechanical ventilation and refrigerant leak detectors is recommended to mitigate risks. Proper refrigerant recovery and training are essential for safely handling the dismantling and disposal stages.

The report identifies R32 and R290 as promising refrigerants due to their lower GWP and satisfactory performance characteristics, though each requires different risk mitigation strategies. R32 offers a favorable balance between performance and environmental impact, but its mild flammability necessitates careful handling and strict adherence to safety protocols. R290 (propane), while having excellent thermodynamic properties and very low GWP, poses significant flammability risks that demand rigorous safety measures during use and maintenance.

The analysis emphasizes the importance of comprehensive safety protocols, including mechanical ventilation, refrigerant leak detectors, and proper personnel training across all life cycle stages. The report highlights the necessity of regulatory compliance and adherence to international standards such as ISO 5149 and JIS B 8623, which ensure that safety measures and performance evaluations meet global benchmarks. Additionally, it underscores the role of innovative technologies and best practices in enhancing the safety and efficiency of heat pump systems using low-GWP refrigerants.

The transition to low-GWP refrigerants is crucial for reducing the environmental impact of heat pump systems. The report concludes that this transition can be effectively achieved by balancing environmental benefits with safety concerns. The LCCP evaluations and risk assessments presented provide a robust framework for selecting and implementing these refrigerants in various applications. Comprehensive safety protocols and adherence to international standards are vital for mitigating risks and ensuring safety across all stages of the refrigerant life cycle.

The detailed analysis in this report serves as a valuable guide for policymakers, industry stakeholders, and researchers, advancing the use of low-GWP refrigerants in Japan and potentially in other regions facing similar challenges. It emphasizes that with the right safety measures and compliance with international standards, the adoption of low-GWP refrigerants can be achieved efficiently and safely, promoting sustainability in the refrigeration and air conditioning industry. This balanced approach ensures that the environmental benefits of low-GWP refrigerants are realized without compromising safety, thus supporting broader efforts to combat climate change and promote sustainable development.

7.2 Review of State-of-the-art Technologies

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7.2.1 Refrigerant regulations in Japan

Japanese laws governing refrigerants include laws that seek to prevent global warming and laws that address the safe use of high-pressure gas. Other laws seek to reduce energy consumption when using refrigeration and air conditioning equipment. Next-generation refrigerants have been developed to satisfy these three laws, and refrigeration and air conditioning equipment must be designed, sold, and used based on these laws.

7.2.1.1 Ozone Layer Protection Act

The Ozone Layer Protection Act was enacted in 1988 as national legislation corresponding to the Vienna Convention for the Protection of the Ozone Layer (1985) and the Montreal Protocol on Substances that Deplete the Ozone Layer (1987). The ozone layer protection law stipulates regulations on manufacturing, exporting, and importing emissions and guidelines for rationalizing the use of the ozone-depleting substances imposed by the Montreal Protocol. Regulation of the production, import, and export of ozone-depleting substances has been legislated as part of the chemical substance oversight system. Specifically, based on the reduction schedule set for each substance listed in the Montreal Protocol Annex, limits are set on production and consumption. At present, both the production and consumption of regulated substances other than HCFCs are, in principle, completely abolished. The production of HCFCs has been banned as of the end of 2019. Due to the Kigali Amendment to the Montreal Protocol, the Ozone Layer Protection Act was revised in 2018 to regulate the production and import of HFCs to fulfill obligations to reduce the production and consumption of HFCs. The two main measures are as follows:

a) The Minister of Economy, Trade and Industry and the Minister of the Environment shall publish production and consumption limits for HFCs with which Japan should comply, based on the Montreal Protocol.

b) Any company that intends to manufacture or import HFCs shall obtain permission from the Minister of Economy, Trade and Industry. Those wishing to import such materials must obtain approval from the Minister of Economy, Trade, and Industry in accordance with the provisions of the Foreign Exchange Law.

Based on the Kigali amendment reduction schedule, the upper limit of production and consumption of HFCs throughout the country will be gradually reduced from 2019 onwards. Production and import volumes are allocated to each company based on past actual volumes. Incentives are awarded when refrigerants with a low GWP are produced to help reduce the production of HFCs throughout the country. To meet stricter reduction obligations after 2029, the development and introduction of green refrigerants with lower GWP and equipment using them will be systematically promoted.

7.2.1.2 Act on rational use and proper management of fluorocarbons

In Japan, refrigerant emissions in the refrigeration and air conditioning field will continue to increase, reaching 40 million tons of CO_2 in 2020 and accounting for about 3% to 4% of total greenhouse gas emissions at that time. Some 60% of HFC leaks from refrigeration and air conditioning equipment occur during use; the rest occur during equipment disposal. Recovery rates for fluorocarbons from end-of-life commercial refrigerators and air conditioners remain low (about 30%). Refrigerant leaks from equipment in use have been found to be much higher than expected due to poor maintenance, aging, and other factors.

In light of all these factors, the government of Japan decided to amend and strengthen the Law Concerning the Recovery and Destruction of Fluorocarbons in order to implement comprehensive measures throughout the life cycle of fluorocarbons. The amended law came into effect on April 1, 2015, as the Act on the Rational Use and Proper Management of Fluorocarbons.

The Act on the Rational Use and Proper Management of Fluorocarbons promotes measures to switch to low-GWP refrigerant and to suppress refrigerant emissions. The basic policy has two major pillars: *rational use* and *adequate management* of fluorocarbons to control emissions of fluorocarbons into the atmosphere. At each stage of the life cycle, from manufacture to disposal of refrigerants, the companies required to take action are clarified and obligations imposed on each company. *Rational use* means producing chlorofluorocarbons with a lower greenhouse effect and reducing their production and consumption. *Adequate management* means controlling total emissions by grasping the state of fluorocarbon emissions. The specific measures for each stakeholder are as follows:

a) Phase down the production of HFCs

Refrigerant gas manufacturers must reduce the production of HFCs, converted to equivalent CO_2, by developing substances with low GWP and regenerating discarded refrigerants.

b) Development of equipment using non-fluorocarbon / low-GWP refrigerants

Manufacturers of refrigeration and air conditioning equipment and HFC-using equipment must introduce products with the lowest environmental impact possible at that time, based on technological progress and market trends. Refrigeration and air conditioning equipment manufacturers must switch to products based on non-fluorocarbon or low GWP fluorocarbons by a specified target year for each product category.

c) Preventing leaks of HFCs from equipment in use

Equipment users or managers must reduce refrigerant leaks via appropriate management during use. Periodic inspections are required based on equipment capacity. In the event of a refrigerant shortage, multiple additional charging of refrigerant is not permitted, and the obligation to make proper repairs applies.

d) Stricter refrigerant recovery

In the disposal of refrigeration and air conditioning equipment, the refrigerant must be properly recovered, and the recovered refrigerant must be destroyed or regenerated without releasing the refrigerant into the atmosphere. Only contractors registered with local governments are permitted to charge and recover the refrigerants used in commercial refrigeration and air conditioning equipment and to destroy the recovered refrigerant.

In accordance with the above basic policy, requirements were established for fluorocarbon manufacturers, fluorocarbon products manufacturers/importers, and commercial refrigeration and air conditioning equipment managers. The target for HFC production in 2030 is 32% lower than the reference year of 2013.

Table 7-1: Target value and year for each designated product

Designated products	Target value (GWP)	Target year
Room air conditioner	750	2018
Commercial air conditioner for offices and stores (with legal refrigeration capacity less than 3 tons)	750	2020
Commercial air conditioner for offices and stores (with legal refrigeration capacity of 3 tons or more)	750	2023
Commercial air conditioner for offices and stores (for central air conditioners using centrifugal chillers)	100	2025
Condensing unit and refrigerating unit (for separate type showcases etc.)	1,500	2025
Cold storage warehouse (for central types with floor area of 50,000 m^2 or more)	100	2019
Mobile air conditioner	150	2023
Urethane foam (for house building materials)	100	2020
Dust blowers	10	2019

7.2.1.3 High-Pressure Gas Safety Act

The most significant challenge in converting to low GWP refrigerants is their weak flammability. There is no promising non-flammable (A1) refrigerant available as an alternative refrigerant for R410A, and all refrigerants with reasonably low GWP are weakly flammable (A2L). The issue is whether the safety of such weakly flammable refrigerants can be ensured or whether the use of these refrigerants meets the safety standards of each country and international safety standards. This points to a trade-off relationship between global warming countermeasures and refrigerant combustibility. Notable international standards include ISO and IEC. EN (European Standard), ASHRAE (American Academic Standard), and GHS (United Nations Standard). The High-Pressure Gas Safety Law regulates the safety of refrigerants for refrigeration and air conditioning equipment in Japan. Since this is a law, not a standard, compliance is mandatory. Table 7-2 shows the international standard, European standard, US standard, and Chinese standard for refrigerant definition and safety.

Table 7-2: Safety standards related to refrigerants in each region

	Refrigeration and Air Conditioning			General Gases (Transportation)
	Refrigerant	RAC total	Equipment	
International	ISO 817	ISO 5149	IEC 60335-2-40,24,89,34	GHS
United States	ASHRAE 34	ASHRAE15 UL1995,484	UL984 UL60335-2-40	DOT
Europe	EN378	EN378	EN60335-2-40	
China	GB/T 7778-2008	GB 9237-2001 SB/T 10345.1-4-2012 (EN378:2008)	GB 4706.32-2012 (IEC 60335-2-40:2005)	
Japan	High-Pressure Gas Safety Act		Japan Electrical Safety Standards	General High-Pressure Gas Safety Ordinance

Standards governing refrigerant flammability include ISO 817, ASHRAE 34, and EN378, as well as the High-Pressure Gas Safety Law in Japanese. Combustion grades differ depending on standards for various reasons. One is the difference in test methods. Since the ignition energy of the Japanese test method exceeds that of other test methods, the Japanese test results in the combustion range are wide. The second point is that the combustion range defined as flammable differs depending on the standards. For example, ISO 817 determines refrigerants with an LFL of 3.5% or less to be flammable, while GHS uses flame propagation as a condition for judgment. Under the Japanese High-Pressure Gas Safety Law, refrigerants with an LFL of 10% or less are combustible. The last major difference is that the international standards define a refrigerant grade of slightly flammable (A2L), while the act on high-pressure gas safety in Japan does not classify slightly flammable [“has no slightly flammable category”]. Only R32, R1234yf, and R1234ze (E) are treated as specific inert gases.

The Japanese Act on High-pressure Gas Safety originally lacked the concept of low flammability, but it was revised in November 2016. The above three gases were defined as specific inert gases close to non-flammable refrigerants. A specific inert gas poses less risk when used in refrigeration and air conditioning equipment. To treat A2L refrigerant as a specific inert gas, the following technical measures must be taken:

a) Refrigerating and air conditioning equipment using the specified inert gas must be structured so that leaked gas does not accumulate.

b) A detection/alarm facility must be installed in places where leaked gas may accumulate.

7.2.1.4 Act on the rational use of energy

The act on the rational use of energy was established in 1979 in the wake of the oil crisis. To help ensure the effective use of fuel resources in accordance with the economic and social environment related to energy, the following measures were taken to contribute to the sound development of the national economy:

- Measures for rational use of energy for factories, transportation, buildings, machinery, and equipment
- Measures for leveling demand for electricity
- Other measures necessary to comprehensively promote the rational use of energy

According to the Japanese government's long-term energy supply and demand outlook, plans call for achieving energy savings of approximately 50.3 million kiloliters of crude oil equivalent in FY2030, with FY2013 as the base year, assuming economic growth at an annual rate of 1.7%. However, large-scale investments in the industrial and business sectors for energy conservation have not progressed, and energy consumption efficiency has not improved. In the transportation sector, as the Internet sales market grows, the need has emerged to promote the efficiency of small cargo transportation. Against this backdrop, the Act on the Rational Use of Energy has been strengthened year by year.

(1) Measures related to factories, etc.

If a company's energy consumption (crude oil equivalent) is more than 1,500kℓ / year, the company must notify the government of the amount used. The company must reduce specific energy consumption by an average of 1% or more annually over the medium to long term by assigning an individual with expertise to an energy management position and by implementing energy saving measures.

Energy conservation standards (benchmarks) to be achieved over the medium to long term are defined for each industry. Each company is divided into three classes based on the results of energy saving, and high-performing companies are publicly announced. Guidance is provided to companies in the lowest energy-saving class.

(2) Measures related to transportation

Energy conservation measures related to transportation include measures for transporters and shippers. Transporters use energy to transport cargo or passengers. Shippers continue to ask freight companies to transport their cargo.

A company with a certain transportation capacity must notify the department in charge of its transportation capacity. It must submit a medium- to long-term plan for the rational use of energy to the Minister of Land, Infrastructure, Transport and Tourism.

Shippers who continue to transport more than a certain amount of cargo must notify the department in charge of cargo and submit a medium- to long-term plan for the rational use of energy to the Minister of Economy, Trade and Industry.

(3) Measures related to machinery and equipment

An energy-saving standard called the Top Runner System has been introduced as an energy-saving measure for machinery and equipment (e.g., automobiles, home appliances, and building materials). Under the Top Runner System, manufacturers and importers of target equipment and building materials are required to achieve various energy consumption efficiency targets and to display their energy consumption efficiency. The target energy-saving standards (Top Runner standards) are determined based on future prospects for technological development, as well as the performance of commercially available products having the highest energy consumption efficiency (top runners).

7.2.2 Past national project initiatives involving low GWP refrigerants

7.2.2.1 Role of new energy and industrial technology development organization (NEDO)

As one of Japan's largest public research and development management organizations, NEDO plays an important role in the country's economic and industrial policies. It has two basic missions: addressing energy and global environmental problems and enhancing industrial technologies.

Instead of employing its own researchers, NEDO coordinates and integrates the technological capabilities and research capabilities of industry, academia, and government. It also promotes the development of innovative and high-risk technologies. NEDO seeks to help find solutions to various social issues and to promote market creation by demonstrating and producing the practical applications of such technologies.

As part of its technology development management, NEDO formulates project plans and establishes project implementation frameworks by combining the capabilities of industry, academia, and government, including public solicitations of project participants. To achieve maximum results, NEDO pursues research and development projects and sets targets based on changes in social conditions.

To help counter global warming, NEDO is promoting technological developments that promote conversion from HFCs to low global warming potential (GWP) substances.

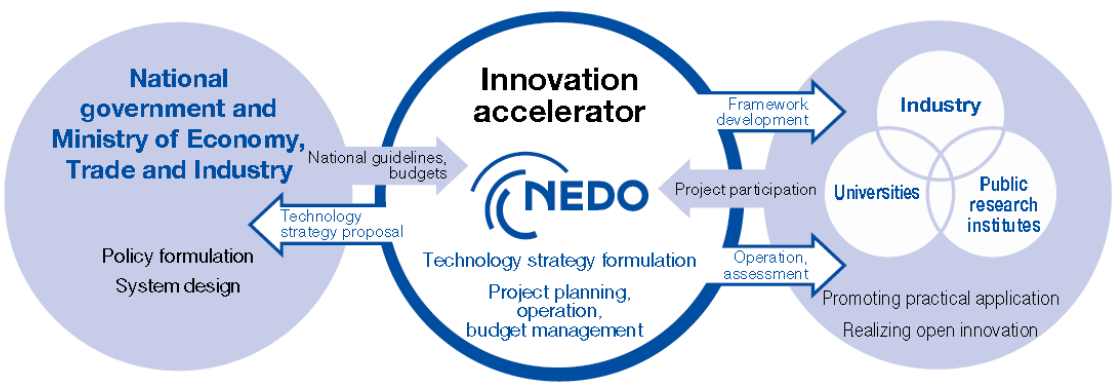

Figure 7-1: Role of NEDO

7.2.2.2 National project to develop low GWP refrigerants

To expand use of high efficiency refrigeration and air conditioning equipment based on low GWP refrigerants, NEDO is developing technologies for both equipment and refrigerants. It is also moving forward with initiatives to promote a shift to low energy consumption and low GWP refrigerants. One important issue is the nature of the risks posed by the new refrigerants and how we can use them safely.

7.2.2.2.1 <u>Development of non-fluorinated energy-saving refrigeration and air conditioning equipment</u>

From FY2011 to FY2015, NEDO undertook a project titled "The Development of Non-Fluorinated Energy-Saving Refrigeration and Air Conditioning Equipment." This project sought to address three themes: developing equipment capable of high-efficiency operations with low-GWP refrigerants, developing highly efficient low-GWP refrigerants, and evaluating the performance and safety of low-GWP refrigerants. In particular, NEDO focused on the safety and risk assessment of mildly flammable, low GWP refrigerants (A2L refrigerants), which had not formerly been used as refrigerants.

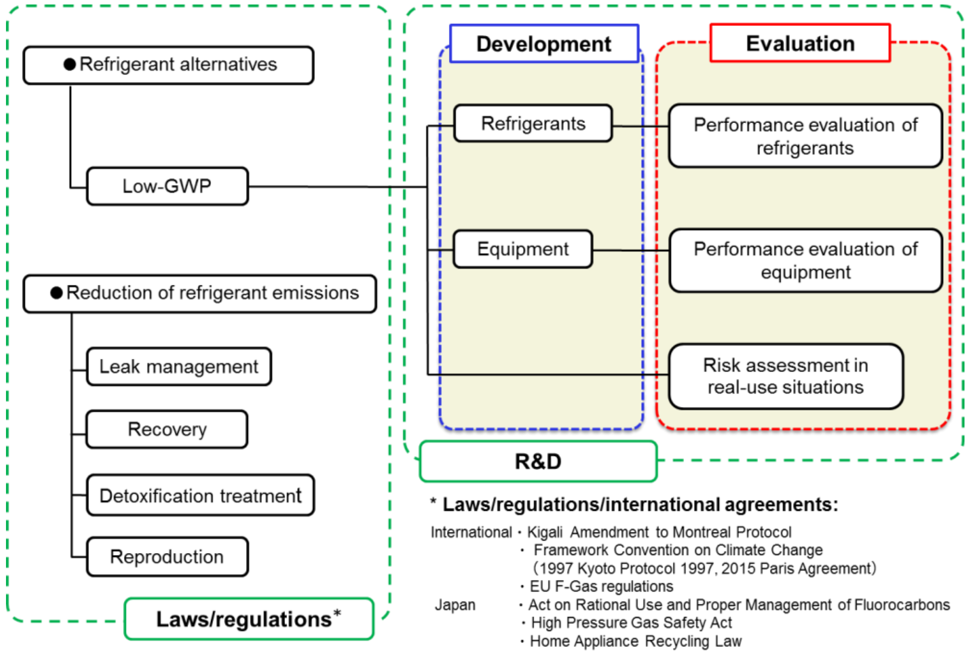

Figure 7-2: HFC countermeasures

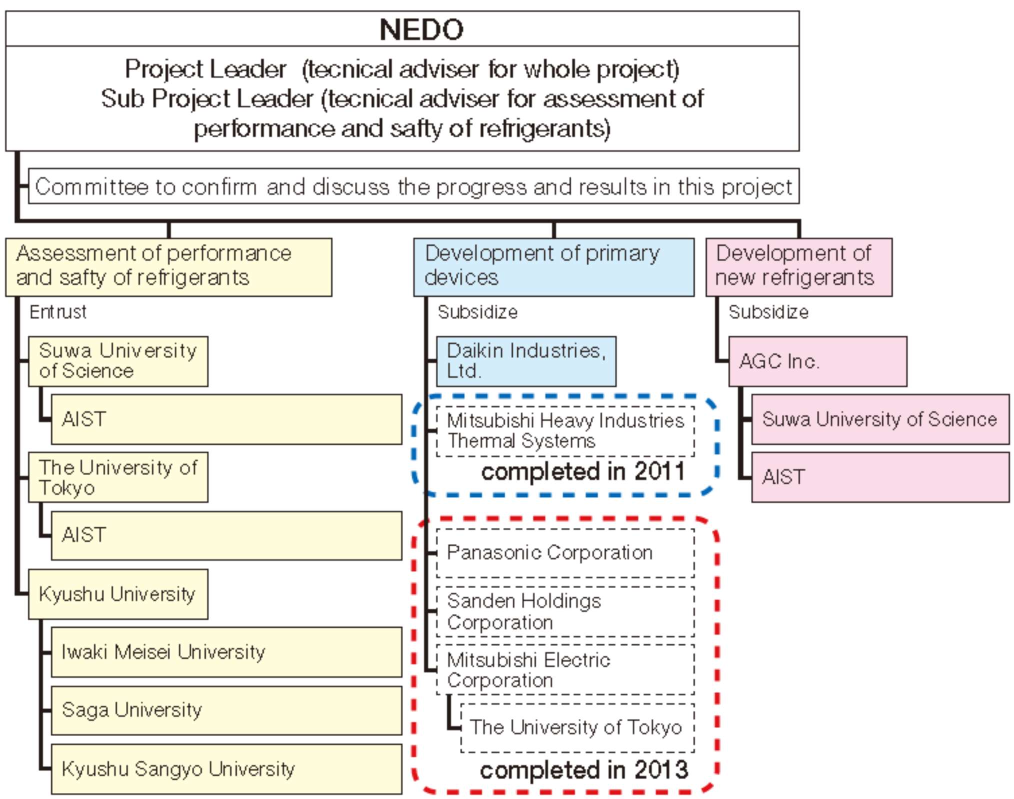

Figure 7-3: R&D implementation system in this project

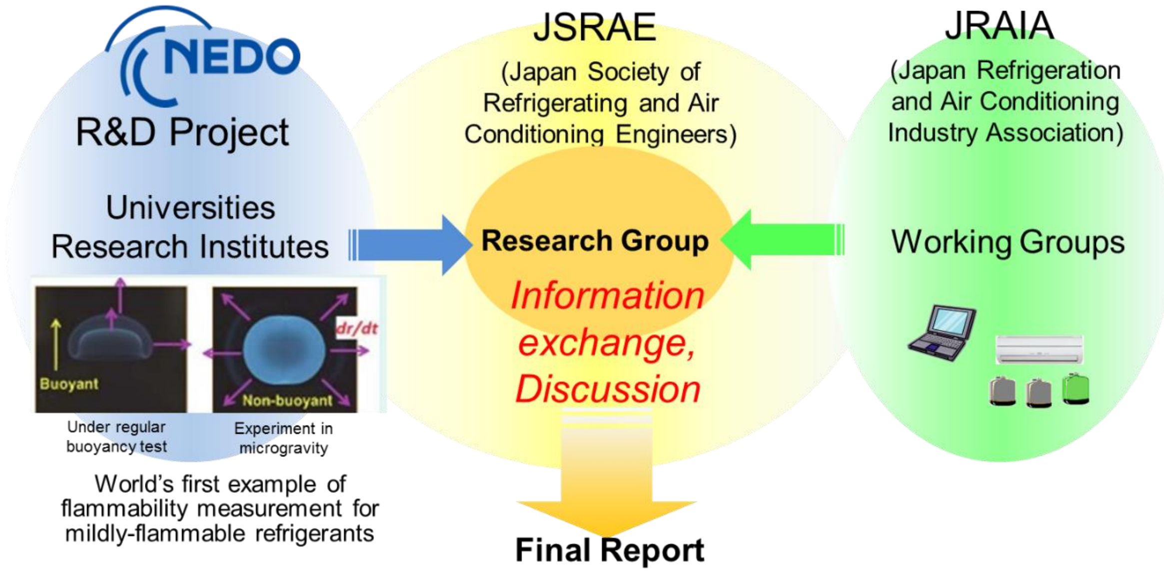

Figure 7-4: Research group composed of industry, academia, and governmental organizations

7.2.2.3 Examples of project achievements

Four results emerged from the "Development of Non-Fluorinated Energy-Saving Refrigeration and Air Conditioning Equipment Systems" project.

7.2.2.3.1 <u>Development of primary devices to achieve high performance with low greenhouse effect refrigerants</u>

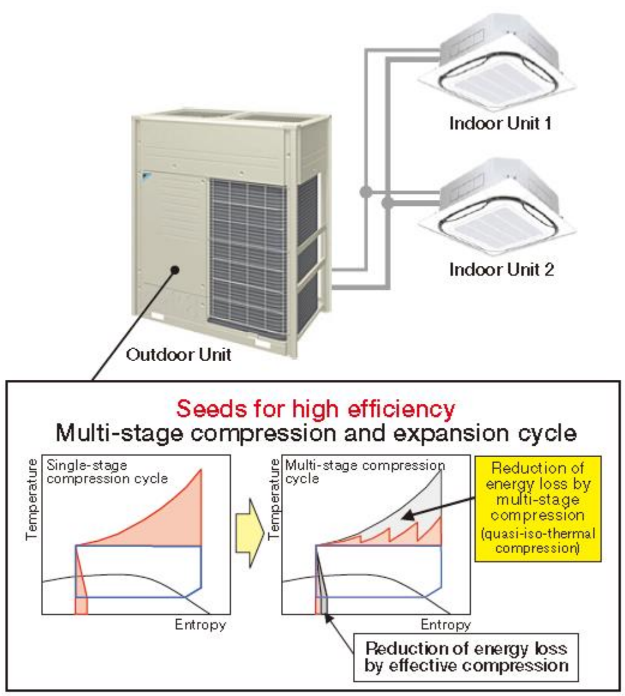

Figure 7-5: High efficiency cycle and unit in test operation

The goal was to achieve performance comparable to conventional products using R410A refrigerants, as measured by cooling rated coefficient of performance (COP), using CO_2 refrigerants in air conditioners. Performance tests were ultimately conducted after installing a novel multi-stage compressor, aluminum micro-channel heat exchanger, composite selector, novel liquid suction heat interchanger, and expander in 5 HP test equipment. Extrapolations of system performance of a 10 HP final product based on observations of this test equipment confirmed all objectives would be achieved. Additionally, cooling-rated COP finally reached as high as 92% of R410A products.

Increased efficiency requires the installation of numerous internal heat exchangers, oil separators, and expanders. The volume ratio was 146% compared to R410A products of equivalent performance.

7.2.2.3.2 Development of new refrigerants with high efficiency and low GWP

This project involved the development of a mixed refrigerant containing HFO-1123 as an alternative to R410A and HCFO-1224yd (Z) as an alternative to R245fa. These new refrigerants feature significantly lower greenhouse gas effects than conventional refrigerants while offering refrigerating performance equivalent to conventional refrigerants.

Table 7-3: Basic performance of the developed refrigerants

R410A = 100%		HFO-1123/HFC-32/HFO-1234yf (40/44/16%)	HFO-1123/HFC-32 (40/60%)
COP	In cooling mode	110%	116%
	In heating mode	96%	99%
APF		96%	97%
GWP		14%	20%

7.2.2.3.3 Results of safety and risk assessments of A2L refrigerants

Low GWP refrigerants are somewhat flammable, which may impede their commercialization. In collaboration with the industrial, governmental, and academic sectors, a study group was established to evaluate the risks posed by mildly flammable refrigerants (A2L refrigerants) and to collect findings related to safety and risk assessments from NEDO projects and risk assessment data held by the Japan Refrigeration and Air Conditioning Industry Association. A report from this study group contributed to the revision of the High-Pressure Gas Safety Act on November 1, 2016, which led to new provisions concerning the use of low GWP refrigerants. The revision, in turn, led to the commercial introduction of a large-capacity centrifugal chiller*1 based on a low GWP refrigerant.

NEDO also developed a method for testing the burning velocity of mildly flammable refrigerants and established a quantitative measurement method to identify the quenching diameter*2 under real-world conditions. In the event of a spark inside the electromagnetic switch in room air conditioners based on mildly flammable refrigerants, the results indicated that the resulting flame would be extinguished at the opening of the relay cover and that the flame would not spread from the cover to the outside if the opening were smaller than the quenching diameter. Based on this result, a revision was proposed of safety requirements for relays in IEC-60335-2-40 (Household and similar electrical appliances - Safety - Particular requirements for electrical heat pumps, air conditioners, and dehumidifiers); the revised edition was published on January 26, 2018.

The results of the safety assessment are expected to help expand the use of mildly flammable refrigerants and related equipment.

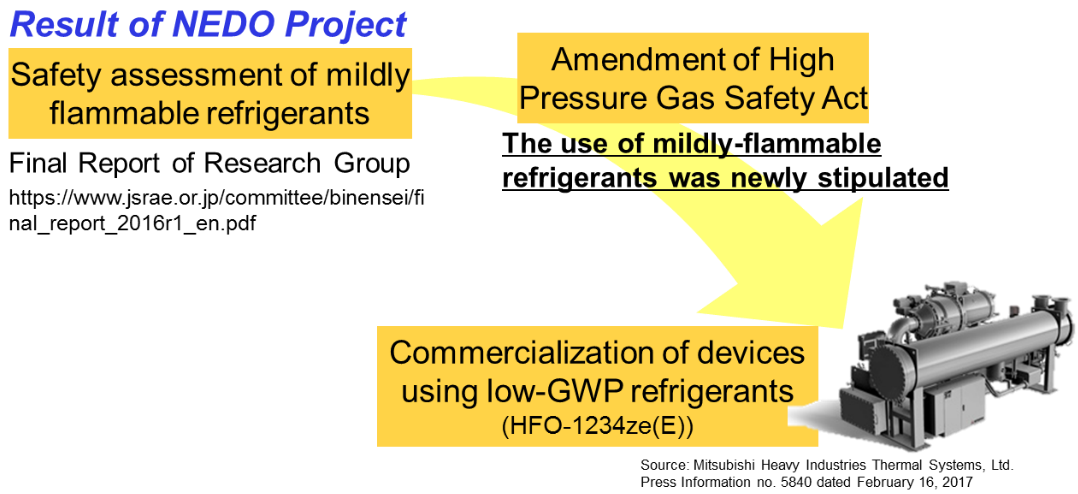

Figure 7-6: Contribution to Amendment of Law in Japan

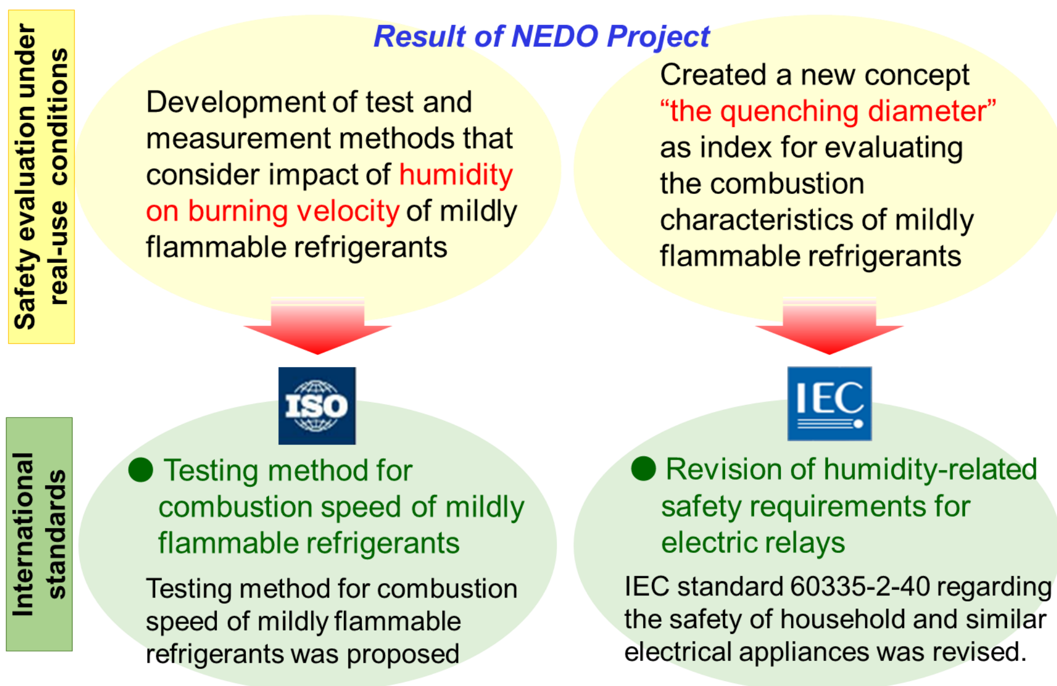

Figure 7-7: Contribution to International Standards

7.2.2.3.4 Registering thermophysical properties of refrigerants in the database

Equations of state for the mildly flammable refrigerant HFO-1123 and the non-flammable refrigerant HCFO-1224yd (Z), which we have developed and investigated in a series of projects, including the "Development of Non-fluorinated Energy-Saving Refrigeration and Air Conditioning Equipment Systems," were registered in REFPROP ver.10, a world thermophysical property database at the National Institute of Standards and Technology (NIST) in the US. This allows performance evaluations and promotes the optimal design of refrigeration and air conditioning equipment using registered low GWP refrigerant, which is expected to contribute significantly to practical applications of new refrigerants.

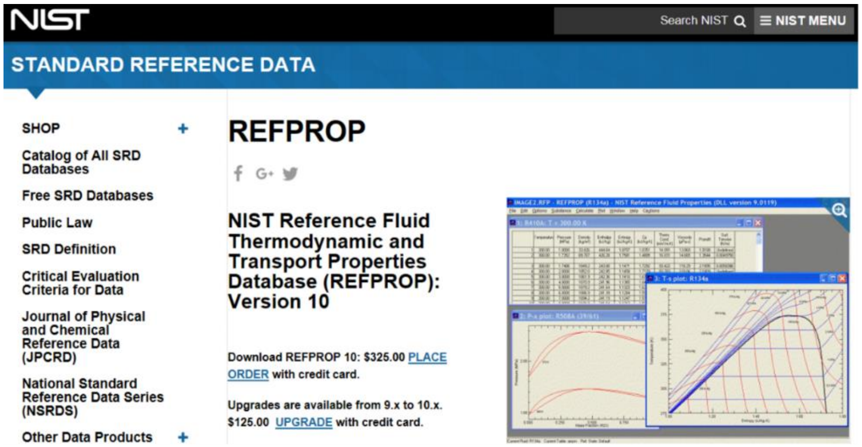

Figure 7-8: REFPROP Version 10

7.2.3 Risk assessment of A2L refrigerants

Risk assessment was carried out for A2L refrigerants R32 and R1234yf used in mini-split air conditioners (residential air conditioners [RAC]), light commercial split air conditioners (PAC), variable refrigerant flow (VRF) systems, and chillers.

7.2.3.1 Risk assessment of A2L refrigerants for single-split air conditioners

7.2.3.1.1 Refrigerant leak simulation

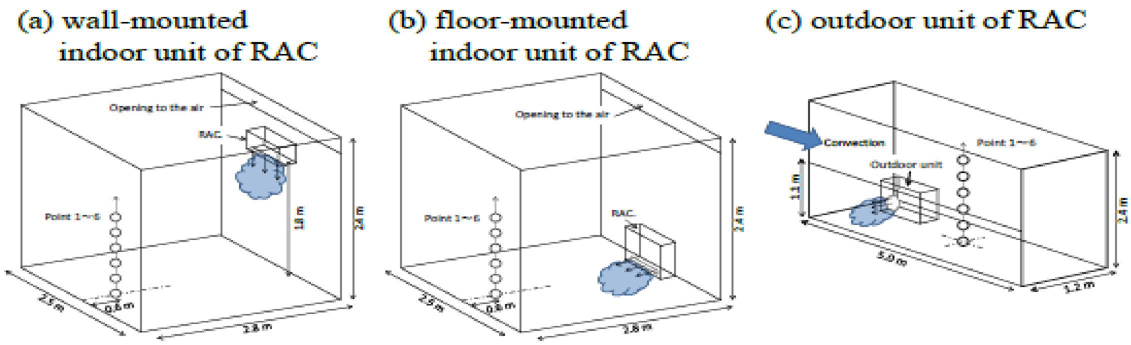

Figure 7-9: Simulation conditions for residential air conditioners

We calculated the time integration of the volume of combustible gas for mini-split air conditioners based on the results of a new simulation carried out at the University of Tokyo in 2012. In the simulation, the boundary conditions were set so that no pressure rise occurred due to refrigerant leakage[1)]. Figure 7-9 shows the calculation area of the indoor wall-mounted, indoor floor-standing, and outdoor mini-split air conditioners in this simulation.

Table 7-4 gives the time integration of the volume of combustible gas of mini-split air conditioners using R32 and R1234yf.

Table 7-4: Time integration of the volume of combustible gas in leakage situations

($m^3 \cdot min$)

	R290	R32	R1234yf
1.1 Logistics	5.50×10^{1}	2.00×10^{-4}	2.20×10^{-4}
2.2 Installation	7.16×10^{2}	2.40×10^{-3}	2.50×10^{-4}
2.5 Mistakes	7.75×10^{-2}	9.00×10^{-3}	1.30×10^{-2}
2.10 Refrigerant charge	8.51×10^{3}	9.97×10^{1}	3.70×10^{2}
3.1 Indoor unit operation	1.41×10^{1}	5.00×10^{-4}	5.50×10^{-4}
3.5 Indoor unit stop	7.16×10^{3}	2.40×10^{-2}	2.50×10^{-2}
4.1 Outdoor unit	7.76×10^{-1}	9.00×10^{-2}	1.30×10^{-1}
5.1 Connecting pipe	8.51×10^{3}	9.97×10^{2}	3.70×10^{3}
7.8 Service/relief	7.75×10^{-2}	9.07×10^{-3}	1.30×10^{-2}
8 Disposal	Using similar situations and values		

7.2.3.1.2 Ignition source evaluation

The progress reports of the Japan Society of Refrigerating and Air Conditioning Engineers for the years 2011, 2012, and 2013 present evaluations and discussions of ignition sources in environments in which a mini-split air conditioner is used. In addition, referring to the reports of Imamura[2)] (Tokyo University of Science, Suwa), Takizawa[3)] (National Institute of Advanced Industrial Science and Technology), and report No. DOE/CE/23810-92[4)] published in 1998 by Arthur D. Little, Inc. (ADL), the assumed ignition sources of residential air conditioners are sparks and open flames.

For R32 and R1234yf, the assumed ignition sources around indoor and outdoor units are sparks from matches or oil lighters, scraping of metal forklift nails, and open flames, such as matches, lighters, and welding torches.

In addition, the amount of refrigerant leakage for residential air conditioners is relatively small. Although the refrigerant may burn in the equipment combustion chamber, the flames are highly unlikely to propagate outside the combustion chamber. Thus, heaters and water heaters are not regarded as potential ignition sources.

(1) Electronic parts as a source of ignition

The DOE/CE/23810-92 report, submitted to AHRI in 1998 by ADL and now available on the website, reported ignition test results for R32 released into an environment in which a mini-split air conditioner is used, and a flammable atmosphere is created. This work examined numerous ignition sources for flammable vapors containing R32. For example, vapor was ignited by the arc of a high-voltage power supply, a high-temperature electric wire, the fire caused by cutting the current of the excessive compressor electric motor of a high voltage of 120 V or 240 V power supply, and open flames. However, sparks from a wall switch, electric motor, electric drill, tungsten-halogen lamp, low-voltage arc, and other electric appliances with a normal current at 120 V failed to lead to ignition. With regard to the spark generated by the electromagnetic contactor in the main circuit, which one can assume would generate the highest energy, the evaluation result of ADL was judged as non-ignition upon 20 opening and closing tests. This differs from the IEC standard. However, the contacts of the electromagnetic contactor used in Japanese products are surrounded by a cover that usually has a very small gap around the contacting point. Recent studies by AIST confirmed that flame propagation does not occur in an electromagnetic contactor with a rated capacity of 12 kVA and is covered with a cover with a gap of approximately 3 mm around the contact point. Although the evaluation of ignition by these electric sparks was mainly observed for the R32, the R1234yf and R1234ze are believed unlikely to ignite even with a larger contact capacity because their minimum ignition energy is larger than that of R32.[5), 6), 7)]

(2) Source of ignition around indoor and outdoor units (mainly for residences)

The presence of the ignition sources varies greatly depending on the usage of the room. Here, we examine ignition sources in residences where residential equipment and kitchen equipment are used.

Open flames:

Gas appliances, candles, firewood, charcoal, tobacco, and lighters serve as ignition sources for flammable refrigerants. An updraft generated by a flame-like gas stove reduces refrigerant concentrations. If the speed of the updraft exceeds the combustion speed of the refrigerant, the flame will immediately expire, thus rendering ignition and flame propagation unlikely.

Ignition device:

A piezoelectric element, magneto, arc of a high voltage transformer assembly, flint system, and nickel-chrome alloy wire are used as ignition equipment for a kerosene and gas apparatus. These types of ignition equipment cannot ignite R32.

Electrical appliance:

Arc discharge sparks generated between contacts when a device with a large inductance is energized, and sparks during a short circuit are considered ignition sources.

Static electricity:

Static electricity is generally created by friction with a synthetic material. The charge correlates with electric capacity, the relative humidity (RH) of the material, and the dielectric breakdown voltage. When a material is charged to about 12 kV at low RH and the electric capacity is set to 100 PF, the electric discharge energy is 7.2 mJ. Under dry conditions—for example, an RH of 7% according to 4-2 of IEC 61000-4-2—the voltage may approach 15 kV. At this voltage, electric discharge energy reaches approximately 11.3 mJ. Usually, the electric discharge between a doorknob and the human body is about 1 mJ during the winter. A roughly equivalent electric discharge occurs upon the removal of clothing. Since the insulation performance of air is 3,000 V/mm, the possibility that A2L refrigerants will be ignited by static electricity is extremely small.

(3) Summary of ignition sources

The ignition sources are summarized as follows:

a) An electromagnetic contactor with no cover ignites at 7.2 kVA or above. However, if a contact is covered with a clearance of 3 mm or less, it will not ignite until 12 kVA is reached. In this context, the low-voltage electrical equipment found in Japanese houses is a highly unlikely ignition source.

b) A lit cigarette will not ignite R32.

c) Static electricity caused by humans rarely causes ignition in daily life.

Based on the above considerations, in the risk assessment, only open flames were considered as ignition sources for outdoor and indoor mini-split air conditioner units using R32 or R1234yf.

7.2.3.1.3 Allowable fire accident probability

The allowable accident probability of household appliances used by general consumers without considering maintenance is 10^{-8} times/year for 1 million units. In other words, an appliance is considered safe even if a fatal accident occurs once every 100 years per unit. The total number of commercial mini-split and domestic air conditioners in Japan is about 100 million. Thus, the allowable accident occurrence rate during use must be less than 10^{-10} times/(unit·year).

7.2.3.1.4 Leakage conditions

In setting leakage conditions, we must identify how many refrigerant leakage incidents occur in one year from all domestic air conditioners in Japan. In response to a questionnaire survey distributed to construction and service companies regarding the number of refrigerant leakage accidents during installation and repairs and the typical use of fire, we obtained approximately 600 responses. The refrigerant leakage accident rate was 0.77% at the time of installation and 0.74% at the time of repairs or maintenance. With regard to use of fire, the smoking rate at the service work site was 1.3%, while the rate of fire usage other than smoking was 4.2%. The average leakage rate of household air conditioners was 0.023%/year.

7.2.3.1.5 Summary of FTA

Table 7-5 presents the results of the risk assessment for the aforementioned mini-split air conditioners. For normal wall-mounted air conditioners, the hazard occurrence probability (ignition rate) in the revised risk assessment is almost 10^{-10} during use and less than 10^{-9} during transportation, installation, and operation. Since each value is below the tolerance value, no further risk assessment tests were carried out.[8)]

Table 7-5: Ignition probability of various refrigerants

(Normal wall-mounted air conditioner)

Risk: Ignition probability			
Life Stage	R32	R1234yf	R290
Logistic	4.1×10^{-17}	4.5×10^{-17}	9.7×10^{-16}
Installation	2.7×10^{-10}	3.1×10^{-10}	3.7×10^{-9}
Use (Indoor)	3.9×10^{-15}	4.3×10^{-15}	5.0×10^{-13}
Use (Outdoor)	1.5×10^{-10}	2.1×10^{-10}	4.9×10^{-13}
Service	3.2×10^{-10}	3.6×10^{-10}	2.8×10^{-7}
Disposal	3.6×10^{-11}	5.3×10^{-11}	4.1×10^{-7}

However, the values for single floor-standing air conditioners and multi-floor-standing air conditioners in the reviewed risk assessment exceed the tolerance value. We investigated door clearances, primarily in Japanese-style homes, to achieve a risk assessment closer to actual use. We also reviewed whether the same tolerance values could be applied to normal wall-mounted air conditioners. Table 7-6 presents the latest risk assessment results.

Table 7-6: Ignition probabilities for various mini-split air conditioners

Risk: Ignition probability			
Life Stage	Normal wall-mounted R32	Single floor-standing R32	Multi-floor-standing R32
Logistics	4.1×10^{-17}	3.6×10^{-11}	1.1×10^{-9}
Installation	2.7×10^{-10}	4.0×10^{-11}	9.0×10^{-9}
Use (Indoor)	3.9×10^{-15}	4.1×10^{-10}	4.7×10^{-10}
Use (Outdoor)	1.5×10^{-10}	8.6×10^{-11}	1.1×10^{-9}
Service	3.2×10^{-10}	2.6×10^{-10}	4.3×10^{-9}
Disposal	3.6×10^{-11}	2.5×10^{-11}	4.1×10^{-10}

The tolerance value for single floor-standing air conditioners was 10^{-9} during use and 10^{-8} during transportation and installation. This almost meets the allowable values.

7.2.3.1.6 Risk assessment and results for wall-mounted single air conditioners

Table 7-7 compares ignition probabilities for an indoor unit for R290 and R32.

Table 7-7: Ignition probabilities for indoor units

Case	R32		R290	
	Before measures	After measures	Before measures	After measures
In use	2.0×10^{-14}-3.7×10^{-10}	1.8×10^{-17}-3.4×10^{-13}	5.9×10^{-09}-1.1×10^{-04}	5.0×10^{-13}-9.5×10^{-09}
During service	1.8×10^{-6}- 9.0×10^{-6}	1.7×10^{-10}-4.0×10^{-10}	1.7×10^{-6}-9.3×10^{-6}	2.3×10^{-7}-5.5×10^{-7}

7.2.3.1.7 Risk assessments and results for multi-split air conditioners

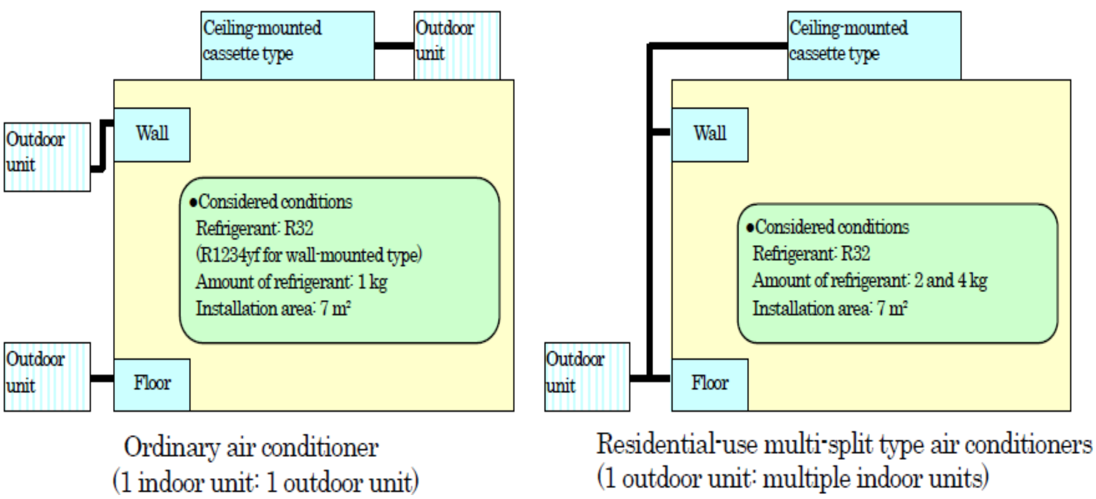

Figure 7-10: Multi-split air conditioners: installation types and analysis conditions

Figure 7-10 shows the installation configuration of a multi-split air conditioner. The indoor units for multi-split air conditioners include wall-mounted, floor-standing, and compact 4-way cassettes.

The allowable fire probability for floor-mounted multi-split air conditioners is set to 10^{-9} times/(unit·year) because the number of units used in Japan is 1% less than for wall-mounted split air conditioners. The probability of accidents during repair and maintenance was set to 10^{-8} times/(unit·year).

Table 7-8: Risk reductions and effects for indoor-use air conditioner

Risk reduction	Method	Reduction effect		
		Max.	Usual	Min.
Delegating risks	No ignition source, Brine cooling without refrigerant in the room	-4	-3	-2
Risk reduction	Reducing the concentration by agitation and exhaust; Safety inter-rock	-3	-2	-1
Safety measures	The detector cuts off the refrigeration circuit and shut off the power	-2	-1	-1
Alarm	The detector sounds an alarm	-1	-1	0
Manual, Sign	Education and training as per manual; sign of attention and alarm; restriction of install area	-1	0	0

A risk assessment of floor-type air conditioners based on FTA was carried out for a 7 m^2 living room for R32 based on the previous assumptions. The results failed to satisfy tolerance values. Table 7-8 gives the S1 countermeasures.

The results of risk assessments based on the FTA of a single floor-standing air conditioner in a floor space of 7 m^2 failed to satisfy tolerances. Countermeasure S1 restricted installation to rooms with a floor area of less than six *tatami* mats (approximately 10 m^2). Table 7-9 gives the results of ignition risk probability calculations, including those for other stages. Adopting measure S1 results in an ignition probability during use of 9.9×10^{-10}, which is below tolerances.

Table 7-9: Ignition risk probability of an air conditioner (with measure S1)

Risk: Ignition Probability		
Type	Representative model	R32 (Measure 1)
Logistics (for each warehouse)	Middle-size warehouse	3.6×10^{-11}
Installation	3.24 m^2 veranda	4.0×10^{-11}
Use (Indoor)	9.9 m^2 room	9.9×10^{-10}
(Outdoor)	3.24 m^2 veranda	8.6×10^{-11}
Service	3.24 m^2 veranda	2.6×10^{-10}
Disposal	3.24 m^2 veranda	2.5×10^{-11}

The countermeasure of restricting the room area is largely determined by the installers. If I kg of refrigerant leaks and diffuses into a room, the concentration of refrigerant will reach 2.7%. Given this possibility, the S2 countermeasure must be further evaluated. The S2 countermeasure means that if a leak is detected, the fan of the indoor unit will be switched on to reduced concentrations below the LFL.

Table 7-10 gives the ignition risk probability for floor-standing multi-split air conditioners with measure S2. The indoor (i.e., during use) ignition risk probability for floor-standing multi-split air conditioners reaches an allowable risk value lower than that of conventional wall-mounted air conditioners (below 10^{-9}) for the same room with a floor area of 7 m^2 and room height of 2.4 m.

Table 7-10: Ignition risk probability of a floor-standing air conditioner (with measure S2)

Risk: Ignition Probability		
Type	Representative model	R32 (Measure 2)
Logistics (for each warehouse)	Middle-size warehouse	3.6×10^{-11}
Installation	3.24 m^2 veranda	4.0×10^{-11}
Use (Indoor)	7 m^2 room	4.1×10^{-10}
(Outdoor)	3.24 m^2 veranda	8.6×10^{-11}
Service	3.24 m^2 veranda	2.6×10^{-10}
Disposal	3.24 m^2 veranda	2.5×10^{-11}

7.2.3.2 Risk assessment for light commercial air conditioners

7.2.3.2.1 Features of light commercial air conditioners

Table 7-11 summarizes the main features of light commercial air conditioners (package air conditioners (PAC)) compared to mini-split air conditioners (residential air conditioners (RAC)) and multi air conditioners for building (variable refrigerant flow (VRF)), from the perspective of the risk assessment of A2L application.

Table 7-11: Comparison of features among different air conditioners

Type	Mini-split (RAC)	Split (PAC)	VRF
Cooling Capacity	2.2–8.0 kW	3.6–30 kW	14.0–168 kW
Amount of Refrigerant	1–2 kg	2–19 kg	5–50 kg
Installation Outdoors: Indoors	1:1–5 (Indoor unit: multiple rooms)	1:1–4 (Indoor unit: all in a single room)	1–3:1–64 (Indoor unit: individual room)
Type of Indoor Units	Wall-mount Floor-standing (low) Ceiling-cassette	Wall-mount Floor-standing (slim) Ceiling-cassette Ceiling-suspended Built-in duct	Wall-mount Floor-standing (perimeter) Ceiling-cassette Ceiling-suspended Built-in duct
Type of Outdoor Units	Air-cooling (horizontal airflow)	Air-cooling (horizontal airflow) Ice thermal storage (horizontal airflow)	Air-cooling (vertical airflow) Ice thermal storage (vertical airflow) Water-cooling
Installation Location (Indoor Units)	Residence	Office Kitchen/Restaurant Factory Karaoke-room (high tightness)	Office Kitchen/Restaurant Factory Karaoke-room (high tightness)
Installation Location (Outdoor Units)	Ground (rooftop) Veranda	Ground (rooftop) Individual floor Semi-underground Narrow space (alley)	Ground (rooftop) Individual floor Semi-underground Machine room
Type of Logistics	Fireproof warehouse	Semi-fireproof medium-	Semi-fireproof medium-

	Small warehouse	sized warehouse Small warehouse	sized warehouse
	Truck Minivan	Truck Minivan (7.1 kW or less)	Truck

The cooling capacity range for PAC is 3.6–30 kW. Accordingly, the amount of refrigerant is 2–19 kg. These values fall in the midpoint range compared to RAC and VRF. As for the amount of refrigerant, since 20% of installations in Japan require pipes longer than 30 m, an additional refrigerant charge on-site is required. With respect to installation, even if one circuit has more than two indoor units, all indoor PAC units should be installed in a single room to safeguard against the possibility that certain units will fail to operate properly if separated. In such cases, the risk of refrigerant leakage into the room is lower than for the VRF system, whose indoor units are installed in several rooms.

For storage and transportation, a PAC outdoor unit for a small store can be treated in the same way as a RAC outdoor unit. Additional evaluations of narrow warehouses and minivan transportation were further conducted. Table 7-12 summarizes high-risk PAC cases.

Table 7-12: High-risk cases of light commercial package air conditioners.

Condition	Risk	Normal cases	High-risk cases
Tubing Length	Large charge amount	30 m or less (chargeless)	Long piping (charge on-site)
Installation Height (IU)	Accumulation of leaked refrigerant	Ceiling: height 1.8 m or more	Floor-standing: 0 m
Installation Location (IU)	Ignition sources	Office	Kitchen
	Ventilation		Karaoke-room (tight)
Installation Location (OU)	Accumulation of leaked refrigerant	Ground	Individual floor
			Semi-underground
			Narrow space
Storage	Accumulation of leaked refrigerant	Fire-protected warehouse	Small warehouse
Logistics	Ignition sources	Truck	Minivan

7.2.3.2.2 <u>Allowable risk levels and probability of refrigerant leaks</u>

Some 7.8 million PAC units (0.6 million units with a product lifetime of 13 years are installed every year) are currently installed in Japan. The possibility that one serious accident will occur every 100 years is deemed an acceptable risk. Workers often handle the equipment when it is not in use. These workers have been trained to control or reduce risks in the event of an accident. Thus, the allowable ignition probability in installation, repair, maintenance, and disposal maybe 10 times that during use.

[Allowable risk levels for PAC ignition accidents]

- Usage stage: 1.3×10^{-9} times/(unit·year); - Logistics, Installation, Service, and Disposal stages (excluding Usage stage): 1.3×10^{-8} times/(unit·year)

Refrigerant leaks from air conditioners are rare. However, if an unexpected leak occurs, the ignition probability is calculated by multiplying the probability of refrigerant leaks, the probability of flammable region generation, and the probability of the presence of an ignition source.

First, the refrigerant leak probability from PAC was determined based on survey results for VRF systems, where equipment design specifications are similar, and questionnaires from PAC manufacturers in the JRAIA. The probability of indoor unit leaks for a PAC was three times that of a VRF. The difference was affected by the levels of leakage checked during installation.

[Probability of refrigerant leaks from a PAC]

- Indoor unit: 1.03×10^{-3} times/(unit·year) for medium-speed leak, 1.50×10^{-5} times/(unit·year) for rapid leak

- Outdoor unit: 6.13×10^{-2} times/(unit·year) for medium-speed leak, 1.34×10^{-3} times/(unit·year) for rapid leak, 1.37×10^{-4} times/(unit· year) for burst leak

In addition, during the product life cycle stages of Installation, Service, and Disposal, leaks are sometimes caused by human error, such as improper use. The probability of human error for a PAC was assumed to be 10^{-3}, which is 10 times greater than for a VRF, since the professional standards met by workers for PAC are lower.

7.2.3.2.3 Ignition source assessment

Two causes can trigger an ignition. The first is the action of the ignition source, such as a spark in a flammable region. The second is the contact between an open flame and a flammable region. However, since triggering factors vary with the ignition scenario, ignition sources were divided into the two categories shown in Table 7-13.

Table 7-13: Ignition sources of A2L refrigerants (Y：Ignited、N：Not ignited)

		Ignition source	R32, R1234yf, R1234ze(E)	R290(ref)
Spark (inflammable region)	Electric Parts	Appliance (cause of a fire)	Y	Y
		Parts in the unit (5 kVA or less)	N	Y
		Power outlet, 100 V	N	Y
		Light switch	N	Y
	Smoking Equipment	Match	Y	Y
		Oil lighter	Y	Y
		Electric gas lighter	N	Y
	Work Tool	Metal spark (forklift)	Y	Y
		Electric tool	N	Y
		Recovery machine	N	Y
	Human Body	Static electricity	N	Y
Open flame (contact with the flammable region)	Smoking Equipment	Match	Y	Y
		Oil or gas lighter	Y	Y
	Combustion Equipment	Heater	Y	Y
		Water heater	Y	Y
		Boiler	Y	Y
		Cooker	Y	Y
	Work Tool	Gas burner (brazing)	Y	Y

In the case of each installation model, we obtained the probability of the presence of ignition sources based on Japanese market statistics. [9), 10)]. Table 7-14 compares indoor installation models for a typical office and a kitchen with abundant ignition sources. The probability of open flame due to appliances was calculated based on the usage rate of each appliance. Spark probability was calculated using the probability of the occurrence of fire accidents caused by appliances, according to the National Institute of Technology and Evaluation (NITE) reports.

Table 7-14: Comparison of the probability of the presence of ignition sources for an office and a kitchen

Ignition source [Units]			Office	Kitchen	
Spark [times /m^{3}min]	Indoor Unit		5.7×10^{-16}	4.5×10^{-16}	P = installed units × accident rate/numbers on market/space volume/(365 × 24 × 60) Fire accident rate: 3 times/year (NITE), numbers on market: 88.4 mil. units
	Appliances	Air Cleaner	7.0×10^{-16}	-	Installed: 0.2 units/room, accident rate: 3.6/year, numbers on site: 17.3 mil
		Humidifier	5.6×10^{-16}	-	Installed: 0.09 units, accident rate: 3/year, numbers on site: 8.11 mil
		Mobile	7.6×10^{-16}	-	Installed: 8.12, accident rate: 23/17 years (LT10year), numbers: 23.9 mil.
		PC	1.2×10^{-14}	-	Installed: 8.12, accident rate: 174/17 years (LT10year), numbers on site: 11.8 mil
		Light	1.3×10^{-15}	1.6×10^{-15}	Installed: 10/15, accident rate: 227/17 years (LT10year), numbers on site: 165 mil
		Tracking	6.7×10^{-16}	1.1×10^{-15}	Installed: 10/15, accident rate: 202/17 years (LT10year), numbers on site: 298 mil
		Refrigerator	-	1.6×10^{-14}	Installed: 0/3, accident rate: 267/17 years (LT10year), numbers on site: 3.88 mil
		Freezer	-	3.8×10^{-15}	Installed: 0/2, accident rate: 16/17 years (LT10year), numbers on site: 0.658 mil
		Dishwashers	-	9.7×10^{-15}	Installed: 0/2, accident rate: 71/17 years (LT10year), numbers on site: 1.511 mil
		Phone	-	2.5×10^{-16}	Installed: 0/1, accident rate: 18/17 years (LT10year), numbers on site: 5.67 mil
		TV	-	1.1×10^{-15}	Installed: 0/1, accident rate: 355/17 years (LT10year), numbers on site: 25.2 mil
		Exhaust Fan	-	5.5×10^{-15}	Installed: 0/4, accident rate: 105/17 years (LT10year), numbers on site: 5.96 mil
	Smoking Equipment (Match/Oil lighter)		8.8×10^{-7}	-	P = smoker presence rate in the room × 0.209 × 17.1/space volume/(24 × 60) × 0.05 Smoker presence in the room: 0.1, smoking rate: 0.209 (Japanese Adult) Smoking numbers: 17.1/day/person(2013JT), use rate Match/Oil lighter: 0.05
	Ignition Equipment (Match/Oil lighter)		-	1.2×10^{-6}	P = 5/space volume/(24 × 60) × 0.05 Using rate for gas burner 5 times/day, Use rate Match/Oil lighter: 0.05
Open flame [-]	Combustion equipment	Water Heater	8.3×10^{-3}	6.7×10^{-2}	[Office] inst.: 0.1, Use rate: 2 h/day, [Kitchen]2, 60 min/day. Installed rate: 0.8
		Heater	-	2.7×10^{-5}	Installed: 0.001 units, Use rate: 4 h/day, 60 day/year
		Kitchen Burner	-	3.1×10^{-1}	Installed: 15 units, Use rate: 0.023. Installed rate: 0.9
		Gas Rice Cooker	-	5.0×10^{-2}	Installed: 2 units, Use rate: 2 h/day. Installed rate: 0.3
		Gas Oven	-	5.8×10^{-4}	Installed: 2 units, Installed rate: 2.9×10^{-4}
		Coffee Siphon	-	8.7×10^{-4}	Installed: 3 units, Installed rate: 2.9×10^{-4}
		Gas Burner	-	6.9×10^{-4}	Installed: 0.5 units, Use rate: 0.2 min/time。10 times/day
		Gas Roaster	-	5.8×10^{-4}	Installed: 2 units, Installed rate: 2.9×10^{-4}

For outdoor installations, Table 7-15 compares ground, individual floor, semi-underground, and narrow space installations. The probabilities of the presence of ignition sources for all installation models at each life stage were calculated.

Table 7-15: Comparison of the probability of the presence of ignition sources for outdoor installations

Ignition Source [Units]			Ground	Individual floor	Semi - Underground	Narrow Space	
Spark [times/ m^3min]	Outdoor Unit		1.4×10^{-14}	9.5×10^{-14}	2.5×10^{-14}	9.1×10^{-14}	P = 5.6/7,800,000/space volume/(365 × 24 × 60) Fire accident rate: 5.6 times/year, numbers: 7.8 mil. units
	Smoking Equipment (Match/Oil lighter)	Worker	3.6×10^{-10}	1.3×10^{-9}	1.7×10^{-9}	1.7×10^{-9}	[Worker] P = Smoking rate(near unit) × service rate × 0.322 × 16/space volume/(24 × 60) × 0.05[spark] × 0.01 Smoking rate (near unit): G: 0.2, EF: 0.1, SU/NS：0.5 Service rate: 0.1 Smoking rate for workers: 0.322(Japanese Male：JT) Cigarette numbers (while working): 16/day (Japan) Use rate for match/oil lighter: 0.05 Rule disregarding rate during work: 0.01 [User] P = User presence rate (near units) × 0.209 × 17.1/space volume/(24 × 60) × 0.05 [spark] × smoking area rate Presence rate (near units): G/SU/NS: 0.05, EF: 0.0125 Smoking rate：0.209, Numbers：17.1/day (Japanese adults), Smoking area rate: EF: 0.5, Other: 0.9
		User	5.6×10^{-8}	5.4×10^{-8}	1.1×10^{-7}	1.1×10^{-7}	
Open flame [-]	Smoking	Worker	6.0×10^{-8}	3.0×10^{-8}	1.5×10^{-7}	1.5×10^{-7}	[Worker] P = Worker presence rate (near units) × 0.1 (service rate) × 0.322 (smoking rate) × 16 (cigarettes) × 5/space volume (seconds/cigarette: open flame appearance time)/(24 × 60 × 60) × 0.01 (manual ignorance rate) [User] P = User presence rate (near units) × 0.209 (smoking rate) × 17.1 (cigarettes) × 5 (seconds/cigarette: open flame appearance time)/(24 × 60 × 60) × smoking area rate
		User	9.3×10^{-6}	1.3×10^{-6}	9.3×10^{-6}	9.3×10^{-6}	
	Boiler		6.6×10^{-4}	2.2×10^{-4}	2.2×10^{-4}	2.2×10^{-4}	P = Use rate × Installed rate Installed rate: 0.1% Use rate for ground: 0.66 (24 h/day, 20 days/month)，for other: 0.22（8 h/day, 20 days/month）

7.2.3.2.4 First stage models (typical PAC models)

The risk assessment for PAC was undertaken in three stages as illustrated below. In the first stage, typical PAC systems were selected as simulation models. In the second stage, high-risk cases for systems with a capacity of 14 kW or less were selected as models (floor-standing indoor units excluded). In the third stage, high-risk cases for all PAC systems 30 kW or less, including floor-standing indoor units, were considered as models.

Table 7-16 shows the conditions for typical PAC models. First, 80% of the PAC systems were installed with a piping length of 30 m or less; thus, no additional refrigerant charge is necessary on-site. The amount of refrigerant was set to the initial charging amount at the factory. Second, a 7.1 kW cooling capacity four-way ceiling-cassette system was selected as the indoor unit. This is the best-selling type on the Japanese market. The installation location was an office with natural ventilation. A 14 kW system was selected as the outdoor unit; the charge amount per installation area was the greatest among all models. The ground installation location was selected for the outdoor unit. No accumulation was considered for leakage gas since all four sides were open. The logistics condition was set to normal truck delivery and fireproof warehouse storage. Since no ignition sources are present in the cargo hold of a truck, truck delivery was omitted from the first-stage model. The ignition source for the warehouse used in the calculations was assumed to be a metal spark caused by a forklift bar.

Table 7-17 summarizes the results of the risk assessments for the first-stage model. The ignition probability was calculated for each product life cycle stage. No safety measures were needed since the ignition probability met allowable risk levels.

Table 7-16: Parameters of the first-stage model

Condition	Type	Location	Feature	Installation space		Capacity (kW)	Piping length (m)	Charge amount (kg)
				Floor area (m^2)	Height (m)			
Indoors	Ceiling-cassette	Office	Opening for natural ventilation	42.3	2.7	7.1	≤ 30	3
Outdoors	Horizontal air flow	Ground	Four sides open	50	2	14.0	≤ 30	4
Storage	Bulk storage	Warehouse	2300 units	1000	−	14.0	−	4

Table 7-17: Results of the risk assessment for the first stage model (R32)

Life stage [allowable level]	Logistics [≦ 1.3×10^{-8}]		Installation [≦ 1.3×10^{-8}]		Usage [≦ 1.3×10^{-9}]		Service [≦ 1.3×10^{-8}]		Disposal [≦ 1.3×10^{-8}]	
Safety measures	without	with	without	with	without	with	without	with	without	with
Office (Indoors)	−	−	6.59×10^{-10}	None	3.37×10^{-12}	None	1.19×10^{-10}	None	3.12×10^{-12}	None
Ground (Outdoors)	−	−	6.73×10^{-10}	None	6.35×10^{-11}	None	2.23×10^{-10}	None	6.05×10^{-11}	None
Warehouse	1.55×10^{-11}	None	−	−	−	−	−	−	−	−

7.2.3.2.5 Second stage models (high-risk PACs)

In the second stage are high-risk PAC systems with a capacity of 14 kW or less (floor-standing indoor units excluded), as summarized in Table 7-18. Table 7-19 summarizes the results of risk assessments for the second stage model. In certain cases, involving outdoor semi-underground installation and narrow-space installations, the ignition probability did not meet allowable levels.

Table 7-18: Parameters of the second step models

Condition	Type	Location	Feature	Installation space		Capacity (kW)	Piping length (m)	Charge amount (kg)
				Floor area (m^2)	Height (m)			
Indoors	Ceiling - cassette	Office	Max charge	42.3	2.7	7.1	75	6
		Kitchen	Ignition source number is large	57.2	2.7	14.0	75	8
		Karaoke-room	Tightness	9.7	2.4	3.6	50	3
Outdoors	Horizontal air flow	Ground	Four sides open	50	2	14.0	75	8
		Individual floor	Three sides closed	3.6	4	14.0	75	8
		Semi-underground	Four sides closed	15.3	3.54	14.0	75	8
		Narrow space	One side (small) open	7.5	2	14.0	75	8
Storage	Floor	Small warehouse	Small space	15	2.7	14.0	—*	8*
Logistics	Delivery	Minivan	Integrated drive set and luggage space	4.65	1.34	7.1	—*	6*

*Disposal stage: maximum amount of charge with an additional charge on-site

Table 7-19: Results of the risk assessment for the second step models (R32)

Life stage [allowable level]		Logistics [≤ 1.3×10^{-8}]		Installation [≤ 1.3×10^{-8}]		Usage [≤ 1.3×10^{-9}]		Service [≤ 1.3×10^{-8}]		Disposal [≤ 1.3×10^{-8}]	
Safety measures		without	with	without	with	without	with	without	with	without	with
Indoors	Office	—	—	6.63×10^{-10}	None	4.20×10^{-12}	None	1.21×10^{-10}	None	3.37×10^{-12}	None
	Kitchen	—	—	6.64×10^{-10}	None	1.03×10^{-10}	None	2.65×10^{-10}	None	2.80×10^{-12}	None
	Karaoke room	—	—	6.77×10^{-10}	None	8.71×10^{-11}	None	1.04×10^{-9}	None	2.04×10^{-11}	None
Outdoors	Ground	—	—	7.53×10^{-10}	None	3.13×10^{-10}	None	5.57×10^{-10}	None	2.60×10^{-10}	None
	Individual floor	—	—	8.49×10^{-10}	None	5.79×10^{-10}	None	1.47×10^{-9}	None	6.81×10^{-10}	None
	Semi UG	—	—	3.60×10^{-7}	4.89×10^{-9}	7.14×10^{-7}	1.68×10^{-10}	1.12×10^{-7}	2.33×10^{-9}	8.68×10^{-8}	9.46×10^{-9}
	Narrow S	—	—	2.77×10^{-9}	None	5.96×10^{-9}	5.77×10^{-10}	1.84×10^{-8}	4.21×10^{-10}	7.21×10^{-9}	None
Logi.	Small WH	1.26×10^{-11}	None	-	-	-	-	-	-	1.22×10^{-8}	None
	Minivan	1.73×10^{-10}	None	—	—	—	—	—	—	6.66×10^{-10}	None

The dominant risk factors were assessed, and practical safety measures were taken to reduce the ignition probability to allowable levels. Table 7-20 summarizes the dominant risk factors and the corresponding safety measures. The dominant risk factors during work are human errors, such as improper refrigerant recovery generating a flammable region; improper wiring of a power supply causing a spark; and the probability of the presence of an open flame, such as a gas burner during brazing. Professional training for workers and a requirement to carry a leak detector during operation are effective safety measures.

In the usage stages, which considers the semi-underground condition if the refrigerant charge amount exceeds the allowable figure (depth ≥ 1.2 m, charge amount > 1/2 × LFL × A (floor area) × 1.2), compulsive ventilation by the unit's fan with stirring (minimum wind speed ≥ 4.0 m/s; depth ≤ 2.0 m; distance between blower outlet and wall ≤ 3 m) or mechanical ventilation are effective ways to reduce refrigerant concentrations. As for installations in narrow spaces, an opening of at least 0.6 m is needed to reduce concentrations to allowable levels.

Table 7-20: The dominant risk factors and safety measures for the second step models.

Dominant risk factors			Usage stage	Installation/ Service stage	Disposal stage
Outdoor Semi-underground (semi-underground depth ≥1.2 m)	Factor	Leakage gas	Presence of ignition sources	Human error	Human error
	Item	Diffusion/ Ventilation	Boiler	Refrigerant recovery Gas burner (Brazing)	Refrigerant recovery Wiring for power supply
	Safety measures	**If charge amount > 1/2 × LFL × A × 1.2 Unit fan operating with leakage detector (Minimum wind speed ≧ 4.0 m/s; depth ≦ 2.0 m; distance between blower outlet and wall ≦ 3 m) or compulsive ventilation device**		Workers professionally trained and equipped with leak detectors	
Outdoor Narrow space	Factor	Leakage gas	Presence of ignition sources	Human error	Human error
	Item	Diffusion/ Opening	Boiler	Refrigerant recovery Gas burner (Brazing)	Refrigerant recovery Wiring for power supply
	Safety measures	**Opening of 0.6 m or more for one side**		**Professional training for workers; carrying leak detectors**	

7.2.3.2.6 <u>Third-stage models (high-risk PAC systems of 30 kW or less, including floor-standing indoor units)</u>

The third stage selected high-risk PAC systems with a capacity of 30 kW or less, including floor-standing indoor units, as listed in

Table 7-21. The maximum piping length of a 30 kW system was 120 m. The amount of charged refrigerant was set to the maximum amount. Moreover, the number of indoor units was four since a higher unit number increases leakage probability.

The floor-standing indoor units were selected under two conditions: a 4.5 kW-class system that requires the least indoor installation space and a 30 kW (four indoor units of 7.1 kW) system that requires the maximum amount of refrigerant. A small ice thermal storage system for the PAC was added to the model. The only additional ignition risk due to the ice thermal storage equipped system is that the required refrigerant amount exceeds that of conventional systems. The ice thermal storage system is subject to the third stage model due to the high ratio of refrigerant amount to the indoor installation space. As typical, a ceiling installation was selected for the indoor unit for office or school use. The amount of refrigerant was set to 9 kg, corresponding to the maximum piping length. The largest capacity for a PAC was 14 kW.

Table 7-21: Parameters of the third stage model.

Condition	Type	Location	Feature	Installation space		Capacity (kW)	Piping length (m)	Charge amount (kg)
				Floor area (m^2)	Height (m)			
Indoors	Ceiling	Office	Max charge	169	2.7	30.0	120	19
		Kitchen	Number of ignition sources is large	80	2.7	30.0	120	19
	Floor	Restaurant	Leakage gas accumulated	14	2.5	4.5	50	3
		Factory	Leakage gas accumulated	100	3	30.0	120	19
Indoors (Ice)	Ceiling	Office	Charge rate	50	2.7	14.0	75	9
Outdoors	Horizontal air flow	Ground	Four sides open	50	2.5	30.0	120	19
		Individual floor	Three sides closed	3.6	4	30.0	120	19
		Semi-UG	Four sides closed	15.3	3.54	30.0	120	19
		Narrow S	One side (small) open	7.5	2.5	30.0	120	19
Storage	Bulk storage	Warehouse	2,300 units (outdoors)	1000	—	30.0	—	7

For evaluations during transportation and storage, PAC was evaluated only at the time of storage in a medium-sized warehouse because no storage was available in the narrow warehouse or during minivan transportation. The initial amount of refrigerant for a 30 kW system was set to 7 kg.

Table 7-22 summarizes the risk assessment results for the third stage model. The ignition probability does not satisfy allowable levels for floor-standing indoor units, outdoor semi-underground, and narrow space installations.

As mentioned previously, the high STPF was likely achieved for the floor-standing indoor unit because the leaked gas tended to accumulate near the floor at high concentrations. During use, the corresponding safety measure of compulsive ventilation with the unit fan operating with a leakage detector near the floor proved effective. For the Service and Disposal work stages, as for the second stage model, professional training for workers and a requirement to carry a leak detector proved effective. As for conditions other than floor-standing indoor units, compared to the second stage, indoor space increases in response to increased refrigerant charge amount. Risks are reduced in such cases.

For outdoor installation models, the environment and space conditions were set to the same value as the second stage. The ignition probability was slightly increased compared to the second stage model, due to the significant volume of refrigerant charge for the same installation space. However, the necessary safety measures were the same as in the second stage, as summarized in Table 7-23.

Table 7-22: Results of the risk assessment for the third stage model (R32)

Life stage [allowable level]		Logistics [≤ 1.3 × 10^{-8}]		Installation [≤ 1.3 × 10^{-8}]		Usage [≤ 1.3 × 10^{-9}]		Service [≤ 1.3 × 10^{-8}]		Disposal [≤ 1.3 × 10^{-8}]	
Safety measures		without	with	without	with	without	with	without	with	without	with
Indoors	Office	–	–	6.61 × 10^{-10}	None	7.61 × 10^{-13}	None	4.82 × 10^{-12}	None	1.90 × 10^{-12}	None
Indoors	Kitchen	–	–	6.75 × 10^{-10}	None	7.97 × 10^{-11}	None	1.65 × 10^{-10}	None	7.33 × 10^{-12}	None
Indoors	Restaurant	–	–	1.70 × 10^{-8}	2.45 × 10^{-10}	9.39 × 10^{-9}	1.00x10^{-12}	9.28 × 10^{-9}	2.81x10^{-9}	2.99x10^{-9}	None
Indoors	*Karaoke*-room	–	–	2.30 × 10^{-9}	None	1.05 × 10^{-9}	None	3.11 × 10^{-9}	None	7.04 × 10^{-10}	None
Indoors	Ice TS			6.68 × 10^{-10}	None	3.62 × 10^{-12}	None	4.10 × 10^{-11}	None	2.79 × 10^{-12}	None
Outdoors	Ground	–	–	8.02 × 10^{-10}	None	2.61 × 10^{-10}	None	5.53 × 10^{-10}	None	7.60 × 10^{-10}	None
Outdoors	Individual floor	–	–	1.00 × 10^{-9}	None	6.15 × 10^{-10}	None	1.48 × 10^{-9}	None	2.01 × 10^{-9}	None
Outdoors	Semi UG	–	–	3.67 × 10^{-7}	5.64x10^{-9}	4.65 × 10^{-6}	1.14 × 10^{-9}	1.18 × 10^{-7}	2.93 × 10^{-9}	1.43 × 10^{-7}	1.59 × 10^{-9}
Outdoors	Narrow S	–	–	5.34 × 10^{-9}	None	8.49 × 10^{-9}	3.97 × 10^{-10}	1.91 × 10^{-8}	4.95 × 10^{-10}	2.61 × 10^{-8}	2.84 × 10^{-9}
Warehouse		8.30 × 10^{-11}	None	-	-	-	-	-	-	3.51 × 10^{-9}	None

Table 7-23: The dominant risk factors and safety measures for the third stage model.

Dominant risk factors			Usage stage	Installation/ Service stages	Disposal stage
Floor-standing indoor units	Item	Leakage gas accumulation	Leakage gas	Human error	-
	Factor	Lack of diffusion/ ventilation	Stirring	Gas burner (brazing)	-
	Safety measures	**Unit fan operating with leakage detector Min airflow: 10 m^3/min and minimum speed: 1.0 m/s)**		**Professional training for workers; requirement to carry leak detector**	
Outdoors Semi-underground (semi-underground depth ≥1.2 m)	Item	Leakage gas accumulation	Presence of ignition sources	Human error	Human error
	Factor	Diffusion/ Ventilation	Probability of boiler presence	Refrigerant recovery Gas burner (brazing)	Refrigerant recovery Wiring for power supply
	Safety measures	**If charge amount > 1/2 × LFL × A × 1.2 Unit fan operating with leakage detector Minimum wind speed ≧ 4.0 m/s; depth ≦ 2.0 m; distance between blower outlet and wall ≦ 3 m) or compulsive ventilation device**		**Professional training for workers; requirement to carry leak detector**	
Outdoors Narrow space	Item	Leakage gas accumulation	Presence of ignition sources	Human error	Human error
	Factor	one side opening (lack)	Probability of boiler presence	Refrigerant recovery Gas burner (brazing)	Refrigerant recovery Wiring for power supply
	Safety measures	**Opening of 0.6 m or more for one side**		**Professional training for workers; requirement to carry leak detector**	

7.2.3.3 Risk assessment for VRF systems

7.2.3.3.1 Characteristics of VRF systems using A2L refrigerants

Table7-24 lists the features of a VRF system. The most distinctive feature of the VRF system is the large refrigerant charge. The entire amount of refrigerant may be discharged from a single indoor unit in the event of a leak. Since refrigerant piping systems typically have numerous connection points, thorough leakage tests were performed under positive and negative pressure. Operator error was deemed less likely since the systems are generally installed by specialists or highly skilled technicians.

The likelihood of refrigerant accumulation depending on the configuration and installation location of indoor units was considered. The ignition source and ventilation conditions were investigated depending on the type of business where the installation occurred.

Table7-24: Features of VRF systems and A2L refrigerants

Comparison of features of a VRF system and single-split system	Risk
➢ A large amount of refrigerant charge can completely leak into one room	↗ up
➢ Numerous joints connecting the refrigerant circuit or parts of valves, vessels and sensors	
➢ Strict check of refrigerant sealing and leaks	↘ down
➢ Highly skilled personnel for installation, repair, and maintenance	
➢ A variety of system configuration – mode-free type, water-cooled or ice-storage type, etc.	Risk should be specified
➢ Wide range capacity of outdoor and indoor units	

Comparison of features of A2L with A2, A3 refrigerants	Risk
➢ Smaller flammable cloud because of larger LFL	↘ down
➢ Type of ignition source is limited because of larger MIE	

7.2.3.3.2 Allowable accident levels and probability of refrigerant leaks

The ignition probability of an allowable risk typically depends on severity. However, since the assessment of the degree of danger was incomplete at the time, we set allowable levels based on the assumption that all fire accidents are serious and fatal. An allowable level is considered to be the occurrence of a serious accident once every 100 years. With approximately 10 million indoor units already deployed, the allowable ignition probability at the time of indoor use becomes 10^{-9} times/(unit·year). The number of units increases four-fold for the time of outdoor use. Thus, we multiplied 10^{-9} times/(unit·year) by four to obtain the allowable ignition probability. Since the number of indoor units connected to an outdoor unit currently averages eight, setting the probability of permissible accidents for the outdoor unit at the time of use to 4×10^{-9} times/(unit·year) adequately accounts for hazards. Except when the equipment is operated, it is handled by service providers, not consumers. Thus, the extent of the danger can be reduced through self-protective measures, even in the event of an accident. For this reason, the allowable probability of an accident was increased by one order of magnitude and assumed to be 10^{-8} times/(unit·year) or less. [11)]

Due to the relative paucity of available samples, it is difficult to obtain leakage probability at different velocities on the scale of parts per million (ppm). Based on all cases of leaks handled by service providers over the course of one year, we estimated the number of leaks in which customers reported white smoke or abnormal odors and the number of cases in which service providers diagnosed leaks as originating from a broken pipe or hole in the heat exchanger or pipe. Allowing for the possibility that not all leakage cases were considered, we calculated the number of rapid leaks by multiplying the number of reported leakage cases by 10 for indoor units and by 100 for outdoor units, for which customers may not readily notice abnormalities. Since no burst leakages were reported, the number of burst leaks for indoor units was assumed to be zero. The remaining leaks were determined to be slow leakages of 1 kg/h or less. For outdoor units, since samples exceeding 10 kg/h of leakage were reported, we calculated that 1/10 of the rapid leak cases were burst leaks. Table 7-25 presents leakage probabilities classified by leakage rates.

Table 7-25: Probability of leakage classified by leakage rate

Number of leaks reports indicating rapid leaks, 2010, Manufacturer B

	White Smoke	Smelled Burning	Holes in Pipe	Nrp
Indoor Unit	0	1	0	1
Outdoor Unit	1	3	3	7

Probability of leak classified in leak rate

		Total	Slow Leak	Rapid Leak	Burst Leak
			～1 [kg/h]	～10 [kg/h]	～75 [kg/h]
Indoor Unit	Distribution Ratio [−]	1	0.986	0.014	0
	Probability of Leak [ppm]	350	345	5	0
Outdoor Unit	Distribution Ratio [−]	1	0.806	0.176	0.018
	Probability of Leak [ppm]	7600	6126	1338	137

【Method】
Leak Probability： Weighted mean value of probability for each JRAIA manufacturer
Number of rapid leaks = Nrp × 10 (indoor) or 100 (outdoor)
Number of burst leaks = Number of rapid leak × 0.1 (outdoor) , 0 (indoor)
Number of slow leaks = Total − (rapid＋burst)

Nrp : Number of leaks as reported by customer or service technician indicating rapid leak, white smoke, smell (customer comment), or breakage or hole in pipe (service technician comment).

7.2.3.3.3 <u>Results of risk assessment and safety measures</u>

(1) Transportation and storage stage

We hypothesized that risks during transportation could be ignored due to the absence of ignition sources in cargo compartments and since refrigerant leaks occurring during loading and unloading would likely dissipate and fail to generate flammable spaces. During storage, the ignition probability was 7.8×10^{-17} to 1.8×10^{-16} times/(unit·year). This is below the allowable value of 10^{-8}.

(2) Installation stage

An indoor unit for ceiling installation was installed in an office with floor space of 40.6 m^2. The outdoor unit was assumed to be a semi-underground unit. The amount of refrigerant was 26.3 kg.

Piping connections during brazing and trial operation, as well as electrical systems, heating systems, and boilers, were considered the primary ignition sources. An ignition source probability was determined for each.

Table 7-26 gives ignition probabilities for each type of work and for the overall operation. The value for the overall operation slightly exceeded the allowable range (10^{-8}). Ignition probability fell from 1.1×10^{-8} to 1.9×10^{-9} times/(unit·year) with the deployment of refrigerant leakage detection devices during brazing work. Thus, the probability was within the allowable range. Carrying a leakage detection device reduces leak probabilities during piping brazing by 1/100. If this device is not used, the probability increases by 1/10; thus, the leak probability was assumed to be 11/100.

Table 7-26: Ignition probability in installation

Indoor unit : Ceiling
Outdoor unit : Semi–underground

Ignition source	Location	Ignition source	Probability of fire accident
Smoking tools	Outdoor unit	Oil lighter, match	1.9×10^{-10} ～ 9.3×10^{-10}
Other than smoking tools	Connecting pipe	Brazing burner	1.3×10^{-7}
	Connecting pipe in test run	Electrical or Heating appliances	2.2×10^{-14}
	Indoor unit in test run	Electrical or Heating appliances	2.4×10^{-18}
	Outdoor unit in test run	Electrical or Heating appliances	1.6×10^{-8}
	Outdoor unit in elevator	Electrical parts	2.8×10^{-22} ～ 1.2×10^{-21}
Total	Above * Frequency of installation		1.1×10^{-8}

(3) Operation stage of indoor units

We investigated the probability of ignition for all standard and severe risk cases. The overall total for the product of the constituent ratio and ignition probability of each case is equal to the probability of the occurrence of an ignition accident in an indoor unit.

Table 7-27 presents the collected constituent ratios and probabilities of ignition occurrence for each assumed case and cases without measures.

The probability of ignition failed to reach the allowable value of 10^{-9} times/(unit·year) for the worst-case scenario, assuming inoperable forced ventilation in severe cases. The target values were satisfied in most cases when forced ventilation was applied based on the Building Standards Law, but further measures are needed for restaurants (floor-standing).

Table 7-27: Ignition probability of indoor units during operation without safety measures

In each installation cases

[time/(unit･year)] Not allowable | Allowable

Installation case						Fire accident probability, A (Without measures)		
Site		Type	Constituent ratio, P	Allowable probability	Ratio of no vent, R	No vent A_1	Vented A_2	Mean $A_m=RA_1+(1-R)A_2$
Indoor	Office	Ceiling	3.8×10^{-1}	1.0×10^{-9}	1.0	7.6×10^{-9} *1)	3.5×10^{-12}	7.6×10^{-9}
	Karaoke	Ceiling	2.1×10^{-3}		5.0×10^{-2}	1.8×10^{-7}	4.4×10^{-11}	9.0×10^{-9}
	Restaurant	Floor	2.0×10^{-2}		2.0×10^{-1}	3.8×10^{-7}	5.4×10^{-9}	8.0×10^{-8}
	Hair salon	Ceiling	1.6×10^{-3}		2.0×10^{-1}	1.3×10^{-9}	1.2×10^{-10}	3.6×10^{-10}
	BBQ restaurant	Ceiling	7.8×10^{-4}		1.0×10^{-1}	2.8×10^{-9}	4.4×10^{-10}	6.8×10^{-10}
	Ceiling space	Ceiling concealed	1.0×10^{-0}		1.0×10^{-1}	3.0×10^{-10}	-	3.0×10^{-11}

Total in market

Total＝Σ(P ∗ A)	4.0×10^{-1}	1.0×10^{-9}	-	1.1×10^{-8}	1.1×10^{-10}	4.5×10^{-9}

***1) Ventilation turned off at night from 18:00 to 09:00.**

For the indoor safety of VRF systems when the rate of refrigerant charge (that is, refrigerant amount/volume of the room) exceeds the values in the ISO 5149 international safety standard, Part 1, devices for leakage detection, ventilation, warning alarms, and refrigerant shut-off devices should be installed.

Table 7-28 presents ignition probabilities when these safety measures are implemented. The effectiveness of the safety measures in lowering risk was established for each installation condition related to mechanical ventilation. However, we assumed 1/50 of the reduction in risk for the shut-off valve and 1/10 of the reduction considering human intervention in warnings. The implementation of measures for mechanical ventilation and shut-off valves was prioritized.

These safety measures are implemented during installation, but their proper implementation is uncertain. Proper implementation requires interlocking with the indoor unit or the integration of detection, ventilation, and refrigerant shut-off devices with the main body of the indoor unit. Important points related to safety measures are listed below.

- Measure A: The refrigerant concentration calculated from the refrigerant charge rate should be below LFL/2.
- Measure B: A refrigerant leak detector and mechanical ventilation equipment must be installed indoors.
- Measure C: A refrigerant leak detector and a refrigerant shut-off device must be installed indoors.
- Measure D: A refrigerant leak detector and an alarm device must be installed indoors.
- Measure E: The refrigerant charge for a single refrigerant system is less than 60 kg.
- For the safety requirements, one of measures A to D was implemented, in addition to measure E.

Table 7-28: Ignition probability of indoor units during operation with safety measures

In each installation cases [time/(unit･year)] | Not allowable | Allowable

Installation case				Fire accident probability			
				Without measures	With measures		
Site		Type	Allowable probability	Mean	Mechanical vent.	Shut off valve	Safety alarm
Indoor	Office	Ceiling	1.0×10^{-9}	7.6×10^{-9}	3.5×10^{-12}	1.5×10^{-10}	7.6×10^{-10}
	Karaoke	Ceiling		9.0×10^{-9}	$\simeq 0$	1.8×10^{-10}	9.0×10^{-10}
	Restaurant	Floor		8.0×10^{-8}	2.6×10^{-10}	1.6×10^{-10}	8.0×10^{-10}
	Hair salon	Ceiling		3.6×10^{-10}	6.8×10^{-12}	7.1×10^{-12}	3.6×10^{-11}
	BBQ restaurant	Ceiling		6.8×10^{-10}	1.5×10^{-11}	1.4×10^{-11}	6.8×10^{-11}
	Ceiling space	Ceiling concealed		3.0×10^{-11}	-	-	-

(4) Safety measures for floor-standing indoor units

We explored safety measures for floor-standing units, which are prone to the creation of flammable spaces above the floor.

If accumulating leaked refrigerant was detected near the floor surface, the indoor fan stirred and diluted the refrigerant by drawing the leaked refrigerant upward by forced convection. This halted the formation of a flammable space.

Allowable refrigerant charge, m_{max}, with a dilution for upward-flow floor standing unit

$$m_{max} = 0.75 \times LFL \times h \times A$$

where all of the following conditions shall be fulfilled

- $v \geqq 0.0048 \times M + 0.748$
- $Q \geqq 3.7$
- $v \geqq -0.35 \times Q + 0.014 \times M + 2.01$

m_{max} : maximum allowable charge [kg]
LFL : lower flammability [kg/m3]
h : ceiling height [m]
If h exceeds 2.2m, h is defined 2.2m.
A : foor area [m^2]
v : outlet velocity [m/sec]
Area of air outlet shall include area of outlet grill
Q : outlet flow rate [m^3/min]
M : molecular weight ($52 \leqq M \leqq 114$)

Figure 7-11: Allowable refrigerant charge with a dilution for upward flow floor standing unit

By performing the same calculations for R32 and R1234yf, we determined the maximum charge amount when the fan is activated after a refrigerant leak is detected in the top-blowing floor-standing indoor unit (Figure 7-11). Lifting a refrigerant higher into the air column requires higher wind speeds and flow rates with greater refrigerant molecular weight. This condition applies when the molecular weight of the refrigerant is between 52 and 114.

(5) Operation stage of outdoor units

For outdoor units, we established four installation patterns: typical, on each floor, in the machine room, and semi-underground. We selected three ignition sources: smoking (match or lighter), electrical sparks from the outdoor unit, and boilers.

We conducted FTA based on the above preconditions and calculated fire accident probabilities for each installation pattern. The results are presented in

Table 7-29. The ignition probability was found to be less than the criterion of 4.0 × 10^{-9} for the typical installation and for installation on each floor. Consequently, no safety measures were needed. However, the refrigerant diffusion velocity for leaks from a semi-underground installation was extremely low; the ignition probability was 1.74 × 10^{-6}, which exceeds allowance levels. In machine rooms, allowance levels were met without safety measures due to continuous ventilation. However, machine rooms may also have closed spaces; hence, ventilation regulations are necessary. Table 7-30 gives the ignition probability for each installation case.

Table 7-29: Ignition probability of outdoor units

	Smoking	Electric spark	Boiler
Usual	9.2×10^{-17}	5.3×10^{-16}	2.1×10^{-11}
Each floor	3.0×10^{-14}	8.5×10^{-14}	3.4×10^{-9}
Semi-underground	3.1×10^{-11}	7.1×10^{-12}	1.7×10^{-6}
Machinery room	5.5×10^{-15}	3.1×10^{-14}	1.2×10^{-9}

Table 7-30: Ignition probability of outdoor units during operation

In each installation cases [time/(unit・year)] Not allowable | Allowable

Installation case				Ignition probability A	
Site		Constituent ratio	Allowable probability	Without measures	With measures
Out-door	Usual	9.4×10^{-1}	4.0×10^{-9}	1.9×10^{-11}	—
	Each floor	5.0×10^{-2}		3.0×10^{-9}	—
	Semi-underground	1.0×10^{-4}		1.7×10^{-6}	2.5×10^{-13}
	Machinery room	6.0×10^{-3}		1.2×10^{-9}	3.2×10^{-9}

Total in market

Total＝Σ(P＊A)		1.0	4.0×10^{-9}	3.5×10^{-10}	1.9×10^{-11}

(6) Safety measures for outdoor units

Leaked refrigerant accumulates in semi-underground and machine room installations. Since the ignition risk is extremely high, regulations for either the refrigerant amount or ventilation flow are needed to prevent the formation of flammable spaces.

1) Semi-underground installation standards

・Semi-underground height less than 1.2 m: no restrictions.

・Semi-underground height more than 1.2 m: $M/A \leq 0.18$ kg/m^2

M: refrigerant charge [kg], A: floor area [m^2].

2) Machine room installation standards

$n = 75/(0.642 \times LFL \times V)$

n: Required ventilation frequency [times/h],

V: Room volume [m^3]

Note: Two basic installations may be adopted for ventilation equipment.

(7) Repair stage

We investigated the risks posed by repairs of outdoor units, indoor units, and piping, which are installed on-site in ceiling spaces. This section will primarily address the results for outdoor semi-underground installations, for which risks are assumed to be high.

The ignition sources were assumed to be 1) brazing burners, 2) smoking by service personnel, and 3) other (for example, electrical sparks, combustion equipment such as boilers, and live electrical work). The sources of refrigerant leaks were as follows: 1) piping cut with a burner (due to insufficient refrigerant recovery or forgotten steps) and 2) sources other than service work (for example, cracks in the piping).

Measure A: Provide training to service personnel (for example, issue instructions to extinguish the burner immediately if a refrigerant leak is noticed during burner work).

Measure B: Require service personnel to carry refrigerant leakage detection devices and to check for refrigerant leaks before and during work.

We calculated ignition probability for the case in which both the abovementioned safety measures were applied in outdoor use (ventilation by an intake duct). The resulting ignition probability was 2.1×10^{-9} times/(unit·year), which is less than the allowable rate (10^{-8}).

In addition to the case of outdoor semi-underground installations, we performed risk assessments for cases involving low risk and high constituent ratios (outdoor/ above ground installation, outdoor each floor installation, and indoor ceiling installations) and in cases characterized by high risk and low constituent ratios (machine room installations for outdoor units, indoor floor-standing installations, and ceiling space installations for piping).

Table 7-31 presents the ignition probability for each case. The risks posed by indoor ceiling installations, outdoor/above-ground installations, an outdoor installation on each floor, and ceiling space installations for piping were all within allowances (10-8); however, those for indoor floor-standing installations and machine room installations for outdoor units exceeded the allowance. In cases where natural ventilation is assured (ISO 5149 Part 3) and the opening is set 30 mm or less above the floor for indoor floor-standing installations and ventilation devices are installed for machine room installations for outdoor units, the risks met allowable levels (10-8), assuming the adoption of the two aforementioned safety measures.

Table 7-31: Ignition probability in servicing

Model case		Ignition probability without measure [1/(unit×year)]		Ignition probability with measure [1/(unit×year)]
Outdoor	Usual	1.4×10^{-9}	➡	1.4×10^{-10}
	Each floor	3.1×10^{-9}		3.4×10^{-10}
	Semi-underground	**3.6×10^{-7}**		2.1×10^{-9}
	Machinery room	**8.6×10^{-7}**		5.4×10^{-9}
Indoor	Ceiling	8.7×10^{-11}		8.8×10^{-12}
	Floor standing	**1.2×10^{-8}**		3.9×10^{-11}
Pipe	Ceiling space	3.0×10^{-9}		3.0×10^{-10}

(8) Disposal stage

We examined risks arising during the dismantling of units and pipes at an installation site. The results were calculated by multiplying existing ignition probability, such as that for the burner, and refrigerant leak probability during refrigerant recovery and for unit dismantling when the removal operation and installation of a new unit are performed simultaneously. The probability during the semi-underground installation for outdoor units was replacement/non-replacement = 7.76×10^{-7} /(3.04×10^{-9}); during machine room installation, this became replacement/non-replacement = 8.07 × 10^{-7} /(5.57×10^{-9}). In the latter case, the risk exceeds the allowance (under 10^{-8}). We assumed the following measures to reduce ignition probability:

Measure A (Training): Provide risk education regarding smoking and the use of combustion appliances; train operators to extinguish burners immediately in the event of a refrigerant leak. This lowers the risk to 1/10.

Measure B (Carrying leakage detection devices): Require operators to carry refrigerant leakage detection devices during work in narrow places. This lowers the risk to 1.09×10^{-1}. (The risk became 1/100 when leakage detection appliances are carried; the probability of forgetting to carry a device is 1/10.)

The results considered the composition ratio for all equipment. The ignition probability was 6.28 × 10^{-10} times/(unit·year) for failure to implement the safety measures and 5.36×10^{-11} times/(unit·year) when the measures were implemented.

7.2.3.4 Risk assessments for chiller units

The heat source systems supplying hot or cold water to central air conditioning systems use hydrofluorocarbon refrigerants like R134a and R410A. Both refrigerants have high global warming potential (GWP) exceeding 1,000, thereby contributing to climate change. Low-GWP alternatives including R1234ze(E), R1234yf, and R32 have drawn significant attention. The subjects of this study included water-cooled chillers installed in machine rooms and air-cooled heat pumps installed outdoors with a cooling capacity ranging from 7.5 kW and above. [12)]

7.2.3.4.1 Features and tasks for the chiller

The chiller is a heat source system that provides cold or hot water as the heat transfer medium; therefore, it is suitable for large-capacity equipment. These systems typically involve a large amount of refrigerant. Chillers are located in machine rooms; this means the refrigerant is also contained in a confined space. The procedure for installing a chiller must ensure no refrigerant leaks occur. For small- or medium-capacity chillers, air tightness tests must be conducted and the refrigerant charged before shipping. A large-capacity chiller, such as a centrifugal water-chilling unit, is normally shipped as a unit from the factory and installed before the completion of airtightness tests and refrigerant charging. The unit is disassembled at the time of shipment and reassembled at the installation site using flanges and joints are charged with refrigerant after reassembly and the completion of airtightness tests. This assembly process does not require brazing or welding. However, all units must be assembled by trained professional engineers in the same manner as the manufacturer. In addition, periodic inspections must be implemented to prevent potential refrigerant leaks after installation.

The chiller location is usually in the machine room or outdoors (for example, on a roof). Both of these areas are limited areas with restricted access. Generally, only trained specialists can access the chiller to conduct operational checks and for maintenance. Therefore, the installation location is isolated and free from risk, which might be caused by unspecified individuals. In addition, the machine room or the outdoor area is far away from other rooms that can be accessed by the public. Based on the risks mentioned above, the possible risks and actions from the RAs are limited while the countermeasures for avoiding or reducing risks should be clear and effective. However, since the machine room may also house other machinery and electrical equipment, these potential risks must be taken into consideration.

The chillers analyzed in this RA were divided into the major categories of water-cooled chillers and air-cooled heat pumps installed outdoors (air-cooled chillers). Minor categories included and centrifugal chillers, screw chillers, and steam compressor chiller units. Table 7-32 gives the basic specifications for the water-cooled chiller and air-cooled heat pump subject to RA. 60 HP class water-cooled chillers and 30 HP class air-cooled heat pumps are considered nominal cases, since they account for the largest number of units shipped from each manufacturer. The cooling capacity of the 60 HP class varies from 170 kW to 180 kW, depending on the manufacturer. To simplify the analysis, we set 170 kW as the standard capacity, since rigorous specifications apply to the volume and amount of ventilation required for machine rooms.

Table 7-32: Basic specifications for the chillers in the risk assessment

Type of chillers	Water-cooled	Air-cooled
Cooling capacity	Approx. 170 kW	Approx. 90 kW
Refrigerant charge	23.4 kg	11.7 kg*
Outer dimensions (W × L × H)	1.28 m × 1.28 m × 1.28 m	1.00 m × 3.00 m × 2.30 m
Installation location	Machine room	Outdoors

*single refrigeration circuit

Six life stages (LSs) were defined, including the overhaul of the chiller term, which was added to the LSs referenced in the RA [15), 16)]. The other five stages are as follows: logistics, installation, usage, repair, and disposal. We evaluated the installation and usage of a water-cooled chiller and an air-cooled heat pump at the respective locations. The ratio of the number of water-cooled chillers to air-cooled heat pumps was determined to be 3:7, based on domestic shipment data. Calculations of accident probabilities omit logistics and disposal, which do not pose user risks.

Table 7-33 lists the target type and LS ratio for each LS.

Table 7-33: Numbers of chillers at each life stage

LS	Target	Ratio		Number of sales	LS ratio
		Air-cooled	Water-cooled		
Logistics	Supplier	Total		9,687	0.0517
Installation	Operator	7	3	9,687	0.0517
Usage	Operator	7	3	134,000	0.7145
Repair	Operator	Total		22,637	0.1207
Overhaul	Operator	Total		1,838	0.0098
Disposal	Supplier	Total		9,687	0.0517

7.2.3.4.2 Probability of presence of flammable space

The probability of the presence of a flammable space is defined as follows:

[Probability of the presence of a flammable space] = [time-dependent volume of flammable space (m^3min)]/ [target space (m^3)] × [525,600 (min/year)]

The probability of the presence of a flammable space depends on the frequency of leaks, the operation rate of mechanical ventilation in each LS, the ratio of numbers of installed water-cooled chillers and air-cooled heat pumps, and other characteristics of LS.

Table 7-34 lists the probability of the presence of a flammable space in each LS and the frequency of leaks.

The following conditions are based on records of chiller installation for RAs:

(a) The time-dependent volume of R1234ze(E) was applied for water-cooled chillers, and R32 was applied for air-cooled heat pumps.

(b) The target space is defined as 109 m^3 in machine rooms and 31 m^3 in the area surrounded by soundproof walls.

(c) Mechanical ventilation is assumed at a frequency of twice an hour. Two ventilators are installed.

(d) The probability of no mechanical ventilation is 1%. It is assumed that no chiller is operating during the assessment in the LSs during installation and disposal. During these stages, the probability of no functioning mechanical ventilation is 50%.

(e) The failure rate for duct fans is calculated to be 2.5×10^{-4} times/(unit·year).

(f) Based on the results for flammable spaces, for a small leak in the presence of ventilation, the probability is defined to be zero.

(g) The flammable time volume at an air velocity of 0 m/s is applied to outdoor installations.

(h) The ratio of the occurrence between air heat exchangers and unit decorative panels is assumed to be 4:3 for leaks from air-cooled heat pumps.

(i) For the LS of logistics, no flammable space is formed by refrigerant leaks because sealed containers have never been used.

Table 7-34: Probability of the presence of a flammable space in each LS

LS		Without ventilation [case/(unit/year)]	Probability of presence of a flammable space, P_{fs} [-]		
			Burst leak	Rapid leak	Slow leak
Logistics	Transportation	-	0	0	0
	Storage in warehouse	0.01	2.64×10^{-10}	5.46×10^{-7}	0
Installation	Carry-in, installation, filling refrigerant and storage	0.5	7.84×10^{-8}	8.26×10^{-6}	0
	Trial	0.01	7.84×10^{-8}	2.33×10^{-7}	0
Usage [machine room]	machine room	0.01	2.64×10^{-10}	5.46×10^{-7}	0
	Air-conditioned room	-	0	0	0
Usage [outdoor]		-	1.12×10^{-7}	9.84×10^{-8}	0
Repair		0.01	7.84×10^{-8}	2.33×10^{-7}	0
Overhaul		0.01	7.84×10^{-8}	2.33×10^{-7}	0
Disposal		0.5	7.84×10^{-8}	8.26×10^{-6}	0

7.2.3.4.3 Assessments of ignition sources

It is necessary to forecast ignition sources for both outdoors and machine rooms in which chillers are installed. Since the analysis indicates the probability of the presence of a flammable space outdoors is negligible, we can forecast the ignition source in a machine room in which a water-cooled chiller is installed while omitting the outdoor case.

Unlike the highly flammable R290 refrigerant, the ignition sources of mildly flammable refrigerants must be determined because they can be ignited by sparks from power sources, static electricity, or lit cigarettes. The study[18)–22)] performed along with the RAs assessed flammability and ignitability. Open flames, metal sparks, and very large electrical apparatus (solenoid switches and breakers) can all function as refrigerant ignition sources. Table 7-35 and Table 7-36 lists modeled sparks and open flames as ignition sources.

Table 7-35: Ignition source apparatus in a machine room (source of sparks)

Category	Spark		
	Ignition Source	Ignition	Remarks
Electrical parts	Home appliance and a small electrical product	N	5 kVA or below
	Electrical part inside equipment	Yes	Solenoid switch with 5 kVA or above
	AC power source	N	Equivalent to quenching distance
	Lighting switch	N	Equivalent to quenching distance
Work tools	Metal spark (folk of a forklift)	Yes	-
	Electrical power tool	N	Small capacity
	Refrigerant recovery apparatus	N	Small capacity
Human body	Static electricity emitted from the human body	N	Minimum ignition energy or less

Table 7-36: Ignition source apparatus in a machine room (using open flames)

Category	Spark		
	Ignition Source	Ignition	Remarks
Smoking supplies	Match	Yes	Ignition = open flame
	Oil lighter	NF	Open flame once ignited
	Electric lighter	N	Spark not ignited
Burning appliance	Electric radiant heater	Yes	Prohibited to use
	Electric fan heater	N	Prohibited to use
	Gas water heater	Yes	Prohibited to use
	Gas boiler (burner)	N	No timing of ignition
	Ventilation duct, boiler surface	N	140°C or below
	Gas cooking appliance	Yes	Prohibited to use
Work tool	Burner for brazing	N	High in gas velocity

Yes: ignited, N: not ignited, NF: no flame propagation

In a boiler or direct-fired absorption refrigerator, the combustion chamber contains an open flame. A fan introduces air from the machine room into the combustion chamber to burn fuel gas. The fan operates when an open flame is present in the combustion chamber. Even if leaked refrigerant gas flows into the apparatus and ignites, the flame in the combustion chamber is not blown back into the machine room. Consequently, there is no possibility of ignition sources for leaked mildly flammable refrigerant. Since rules bar taking an apparatus such as a stove or an oven into the machine room, these are excluded from the list of ignition sources. Considering the work at each LS and the potential equipment, we calculate the likelihood of the presence of an open flame P_{Ii}. Table 7-37 lists the total probabilities $\Sigma_i P_{Ii}$ of ignition sources for each P_{Ii} and LS.

Table 7-37: Probability of the existence of an ignition source in each LS

LS		Electrical part inside equipment	Metal spark	Match	Oil lighter	Electrical Radiant heater	Gas water Heater & Gas cooking appliance	Other	Total $\Sigma_i P_{Ii}$
Logistics	Transportation	-	1.67×10^{-4}	4.72×10^{-9}	1.18×10^{-6}	-	-	6.35×10^{-8}	3.36×10^{-2}
	Storage in warehouse	-	8.33×10^{-5}	4.72×10^{-9}	1.18×10^{-6}	3.33×10^{-2}	-	6.35×10^{-8}	
Installation	Carry-in, installation and storage	-	8.33×10^{-5}	9.04×10^{-9}	2.25×10^{-6}	3.33×10^{-2}	-	1.47×10^{-6}	3.63×10^{-2}
	Trial	2.87×10^{-3}	-	9.04×10^{-9}	2.25×10^{-6}	-	-	1.47×10^{-6}	
	Filling refrigerant	8.05×10^{-4}	-	4.52×10^{-9}	1.13×10^{-6}	3.33×10^{-2}	-	6.08×10^{-8}	3.41×10^{-2}
	Online*1	1.05×10^{-2}	-	4.72×10^{-9}	1.18×10^{-6}	-	-	6.35×10^{-8}	8.78×10^{-2}

Usage [machine room]	Offline*1	1.05×10^{-2}	-	4.72×10^{-9}	1.18×10^{-6}	-	-	6.35×10^{-8}	
	Online*2	2.50×10^{-4}	-	4.72×10^{-9}	1.18×10^{-6}	3.33×10^{-2}	1.18×10^{-6}	6.35×10^{-8}	
	Offline*2	-	-	4.72×10^{-9}	1.18×10^{-6}	3.33×10^{-2}	1.18×10^{-6}	6.35×10^{-8}	
Usage [outdoor]	Online	1.16×10^{-2}	-	4.72×10^{-9}	1.18×10^{-6}	-	-	1.41×10^{-6}	1.25×10^{-2}
	Offline	9.00×10^{-4}	-	4.72×10^{-9}	1.18×10^{-6}	-	-	1.41×10^{-6}	
Repair	Piping work	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	2.05×10^{-1}
	Cutting work	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Discharging refrigerant	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Detecting of refrigerant	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Charging refrigerant	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Checking and repair	8.54×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
Overhaul	Takedown	8.05×10^{-4}	8.33×10^{-5}	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	1.70×10^{-1}
	Refrigerant recovery	8.05×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	After refrigerant recovery	-	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Setup	8.05×10^{-4}	8.33×10^{-5}	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
	Filling refrigerant	8.05×10^{-4}	-	3.62×10^{-9}	9.00×10^{-7}	3.33×10^{-2}	-	4.86×10^{-8}	
Disposal	Refrigerant recovery	8.05×10^{-4}	-	4.52×10^{-9}	1.13×10^{-6}	3.33×10^{-2}	-	6.08×10^{-8}	1.35×10^{-2}
	After refrigerant recovery	-	-	4.52×10^{-9}	1.13×10^{-6}	3.33×10^{-2}	-	6.08×10^{-8}	
	Dismantling	8.05×10^{-4}	8.33×10^{-5}	4.52×10^{-9}	1.13×10^{-6}	3.33×10^{-2}	-	6.08×10^{-8}	
	Take out	-	8.33×10^{-5}	4.52×10^{-9}	1.13×10^{-6}	3.33×10^{-2}	-	6.08×10^{-8}	

*1: In machine room *2: In air-conditioned room

7.2.3.4.4 Probability of refrigerant leaks

According to a refrigerant leak accident report[17)] released by the High-Pressure Gas Safety Institute of Japan (KHK), 59% of a total of 76 accidents involved leaks from small piping, joints, or valves. Only 1% of the leaks involved vessels. Since the leaks were similar to those from multi-packaged air conditioning unit systems, they were categorized as burst leaks, rapid leaks, or slow leaks, as described in JRA-GL13.[23)] The six leaks categorized as burst leaks were attributable to the breakage of small-bore pipes caused by vibration or slight cracks in the pipes during maintenance work. The seven rapid leaks originated from damage to heat exchanger tubes during maintenance work. In both the burst and rapid cases, the refrigerant leaked as a gas. The other sixty-three slow leaks resulted from deterioration of sealing materials, cracking, or insufficient tightening of joints, corrosion, deterioration of pinholes, or other.

The report was compared to maintenance data[24)] from each company participating in the SWG. The probability of the occurrence of a refrigerant leak (P_l) in each leakage category was calculated for water-cooled chillers, air-cooled heat pumps, and centrifugal water chilling units, based on proportional available data calculated from past shipment data for each company from 2004 to 2011 (Table 7-38). Compared to refrigerant leakage accidents, the total for burst leaks and rapid leaks was at the same level—not lower than 1×10^{-4} times/(unit·year). Thus, the data were considered trustworthy. Burst and rapid leaks from centrifugal chilling units with significantly more refrigerant have not occurred because slow leaks were repaired during maintenance work.

Table 7-38: Probability of leaks, 2004-2011

2004 - 2011 Fy	Probability of the occurrence of refrigerant leaks (times/(unit·year))			
	Water-cooled chiller	Air-cooled heat pump	Centrifugal chiller	Total
Burst leak	5.83×10^{-6}	1.35×10^{-5}	0	1.07×10^{-5}
Rapid leak	1.07×10^{-4}	1.87×10^{-4}	0	1.56×10^{-4}
Slow leak	1.64×10^{-3}	2.21×10^{-3}	7.09×10^{-3}	2.27×10^{-3}

7.2.3.4.5 Calculation of probability of accidental fires

The conditions below are provided to avoid underestimating the frequency of accidents.

(a) Four units of equipment are typically installed in the machine room. The startup/shutdown frequencies of the chiller and pumps are also considered.

(b) All units installed outdoors are surrounded by soundproof walls; a flammable space in the case of a leak from the lower units is considered.

(c) Ignition sources are assumed to be evenly distributed throughout the entire flammable space, including the floor surface. This includes, for example, the case of a lighter flame at ground level.

(d) The probability of the presence of a flammable space in a space lacking ventilation is defined to be equal to the probability of refrigerant leaks.

Table 7-39 (a) shows the technical requirements for safety in detail in the next section. The probability of the occurrence of a fire accident is 3.89×10^{-12} times/(unit·year), assuming reasonable mechanical ventilation systems. This is based on a summary of water-cooled chillers in machine rooms and air-cooled pumps with sound-proof walls. The failure rate was assumed to be 2.5×10^{-4} times/(unit·year) for mechanical ventilation, which is much lower than the probability of once every ten years and still meets safety requirements.

Table 7-39 (b) shows the accident rate without mechanical ventilation, assuming $P_{fs} = 1.32 \times 10^{-4}$ times/(unit·year). If a mildly flammable refrigerant leaks, a flammable area is formed with a higher accident value. If the rate of machine rooms without mechanical ventilation or insufficient ventilation is 1%, the accident rate increases to 1.32×10^{-6} times/(unit·year), which is unacceptable for users. If 1% of machine rooms lack ventilation, the probability is 1.32×10^{-6} times/(unit·year), which is also unacceptable for users.

Table 7-39: Probability of accidental fire

(a) With ventilation

	LS	LS ratio *R*	With ventilation [times/(unit·year)]	
			LS	LS under user's management
Suppliers	Logistics	0.0517	1.51×10^{-13}	-
Operator	Installation [carry-in]	0.0517	2.39×10^{-12}	3.89×10^{-12}
	Installation [trial]	(0.0023)		
	Usage [machine room]	0.2144	4.97×10^{-13}	
	Usage [outdoor]	0.5002		
	Repair	0.1207	1.00×10^{-12}	
	Overhaul	0.0098		
Suppliers	Disposal	0.0517	9.22×10^{-12}	-

(b) Without Ventilation

	LS	LS ratio *R*	Without ventilation [times/(unit·year)]	
			LS	LS under user's management
Suppliers	Logistics	0.0517	4.28×10^{-6}	-
Operator	Installation [carry-in]	0.0517	4.66×10^{-6}	1.32×10^{-4}
	Installation [trial]	(0.0023)		
	Usage [machine room]	0.2144	6.19×10^{-5}	
	Usage [outdoor]	0.5002		
	Repair	0.1207	6.51×10^{-5}	
	Overhaul	0.0098		
Suppliers	Disposal	0.0517	1.72×10^{-5}	-

7.2.3.4.6 Technical requirements for safety

This section describes the "Guideline of design construction for ensuring safety against refrigerant leaks from chiller using lower flammability (A2L) refrigerants," the JRA GL-15[2016] document specified by JRAIA, referring to the safety standards EN1127-1[13)] and IEC 60079s[14)] for flammable gas.

(1) Ventilation

Since the refrigerant is heavier than air, A2L refrigerant leaking into a machine room tends to be confined to the lower part of the room. Typically, an exhaust port would be installed at the lower section of the room, while the air supply is pushed from a point higher than the top of the chiller.

Guidelines specify that the ventilation frequency should be more than 4 times/h regularly. For machine room volumes of 192 m^3 or more, the ventilation frequency should be 2 times/h or more.

However, if the average concentration of refrigerant leaks from the refrigeration equipment does not exceed LFL/4, no compulsory mechanical ventilation requirements apply since there is minimal danger of a fire accident. The guidelines state that it is desirable to ensure the ventilation frequency of 2 times/h or more for the above case.

As a measure to reduce the risk of ventilator failure, the mechanical ventilator is composed of two systems, each of which ventilates twice per hour.

(2) Explosion-proof

For A2L refrigerant, machines with a surface temperature of 700 °C or an electrical apparatus with a capacity of less than 5 kVA are not ignition sources; further, no flammable space is formed if the necessary ventilation is deployed. Therefore, the guidelines require mechanical ventilation. Electrical components equipped with ventilation are not required to be explosion-proof.

For refrigeration equipment using A2L, to safeguard against the event of refrigerant leaks, the refrigeration equipment should be equipped with a decorative panel with an opening of the appropriate area or an exhaust fan to prevent the creation of hazardous areas inside the refrigeration equipment.

(3) Refrigerant gas leakage detection alarm equipment

Although two ventilation devices systems are provided to avoid the risk of failure of the machine room ventilation device, the risk of simultaneous failure of the two systems remains non-zero. Thus, a refrigerant gas leakage detection alarm facility is deployed.

Since the detection alarm equipment must be fully operational, a separate power supply (including a battery back-up power supply) must be provided for the chiller and ventilation equipment. If a refrigerant leak is detected, a warning entailing both a light (lit or flashing lamp) and a sound (warning sound such as a buzzer) must be issued in places where people gather.

7.2.3.5 References

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7.2.4 Compliance initiatives taken in Japan

7.2.4.1 Initiatives to adopt low GWP refrigerants in Japan

7.2.4.1.1 Proactive measures to reduce GWPs

There is urgent demand in Japan to examine ways to reduce the global warming potential (GWP) of the refrigerants used in refrigerating and air conditioning equipment. Nevertheless, many issues remain to be resolved in selecting the most appropriate refrigerant. In recent years, many have advocated for the use of natural refrigerants like CO_2 and HC, based solely on the GWP values of refrigerants, which are known to have a direct impact on global warming; others have stressed the importance of energy-saving performance in mitigating global warming since this aspect affects if indirectly, the amounts of carbon dioxide discharged from operating air conditioners. In addition, it is essential to examine safety when promoting widespread use.

In Japan, it was commonly thought that it would take a long time to identify an ideal refrigerant that would be safe to use, have high energy-saving performance and low impact on global warming, and boast a low GWP to cause minimal direct effect on global warming. Therefore, efforts have been made to promote the widespread use of R32 refrigerant energetically and ahead of others in the world by establishing a technology that would enable optimal use of R32 refrigerant (although it is mildly flammable), which has a GWP one-third that of the conventional R410A refrigerant used in air conditioners while offering high energy-saving performance, thereby reducing adverse effects on global warming as quickly as possible.

The use of CO_2 refrigerant in products other than air conditioners began in 2003, starting with domestic heat pump water heaters. Today, CO_2 refrigerant is used in more than 6 million units. The use of CO_2 and NH_3 is also actively promoted for refrigerating equipment.

This chapter describes the commercial introduction of low GWP products in Japan, focusing in particular on the growing adoption of R32 refrigerant in air conditioning products.

7.2.4.1.2 Switch to R32 for room air-conditioners and commercial air-conditioners

Various efforts have sought to promote a transition to R32 refrigerant for room air-conditioners, and commercial air-conditioners have been confirmed safe for use with R32. As shown in Figure 7-12, as of 2018, the shift to R32 has been completed for almost all room air-conditioners and for more than 70% of commercial air-conditioners of 6 HP or less.

The technology required to use R32 refrigerant is diffusing not just in Japan but across the world. Figure 7-13 shows the growing ratio of R32 air conditioners in global markets.

In Japan, manufacturers have wrapped up efforts to develop basic technologies for R32 refrigerant and have moved on to improve equipment performance and expand the genres of equipment capable of using R32. Current development efforts focus on improving energy-saving performance and increasing operating temperature range and capacity range.

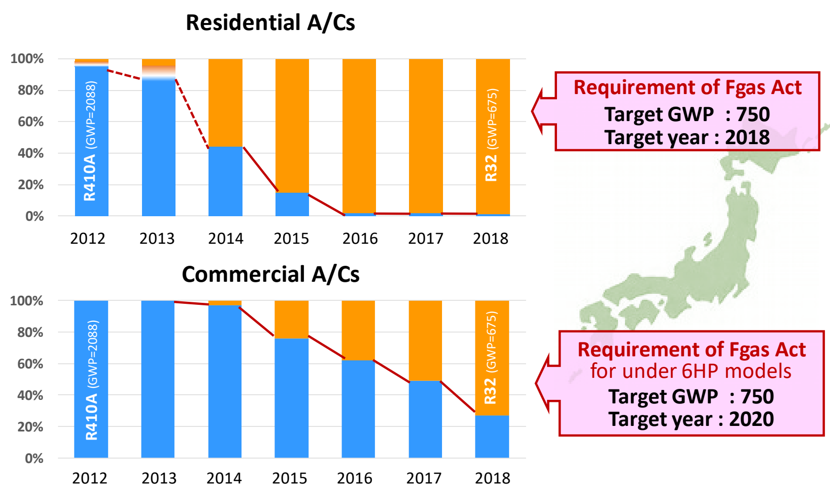


Figure 7-12: Ratio of R32 products in global markets

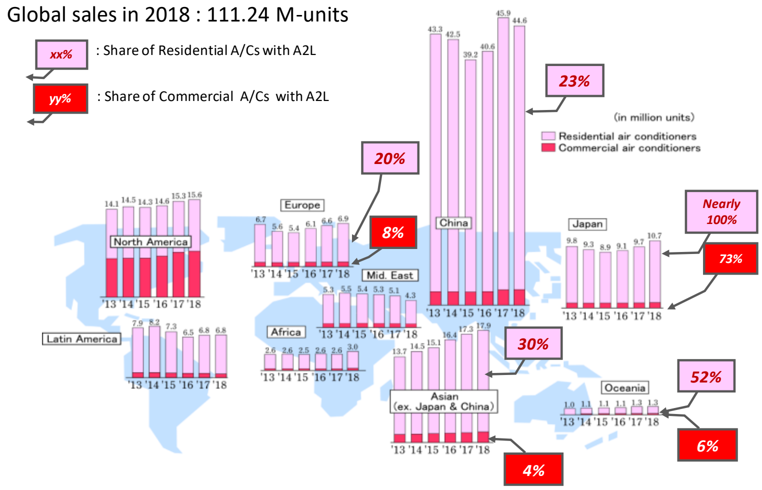


Figure 7-13: Switching to R32

Research on refrigerants with super-low GWPs and utilization of natural refrigerants may be needed to further reduce GWPs. As for expanding the use of natural refrigerants, many issues remain to be addressed and resolved. Continuing research and studies are required to meet growing expectations for increased use of natural refrigerants.

7.2.4.2 Overview of products using low GWP refrigerants in Japan

7.2.4.2.1 Room air-conditioners and commercial air-conditioners (for commercial and office use)

In Japan, the shift in refrigerants from R410A (GWP2088) to R32 (GWP675) has been completed for almost all room air-conditioners and for 73% of commercial air-conditioners. Since each manufacturer's product lineup is extensive, details are omitted here. The manufacturers have completed their refrigerant application technology development phases and initiated development activities to improve the energy-saving performance and comfort-enhancing performance of their products through system optimization.

Manufacturer brand names of R32 room air-conditioners

◆ Panasonic ◆ Daikin Industries ◆ Mitsubishi Electric

◆ Hitachi Johnson Controls ◆ Toshiba ◆ Mitsubishi Heavy Industries

◆ Fujitsu General ◆ Corona ◆ Sharp ◆ Chofu

Manufacturer brand names of R32 commercial air-conditioners (for commercial and office use)

◆ Daikin Industries ◆ Mitsubishi Electric ◆ Hitachi Johnson Controls

◆ Panasonic ◆ Toshiba ◆ Mitsubishi Heavy Industries ◆ Fujitsu General

Examples of technologies introduced for R32 refrigerant and incorporated into Panasonic's room air-conditioners and Toshiba Carrier, Johnson Controls-Hitachi and Fujitsu General's commercial air-conditioners are provided below. The attached reference document describes the features of these products in detail.

Representative examples of technological developments are described below.

(1) Increase in room air-conditioner capacity

The maximum capacity of R410A room air-conditioners was once 8.0 kW. However, in 2014, manufacturers took advantage of the characteristics of R32 to release room air-conditioners with capacities of up to 9.0 kW.

(2) Heat exchanger development examples

(a) Shape of indoor unit heat exchanger

Initiatives are underway to develop an optimal heat exchanger shape: for example, adopting bow-shaped, integrally molded fins to maximize heat exchange efficiency in limited spaces.

(b) Diameter of indoor unit heat exchanger tube

Heat exchange efficiency is being improved by combining tubes with different diameters ranging from 4.0 to 7.94 mm, based on the status of the refrigerant inside the heat exchanger, for the purpose of optimizing refrigerant flow velocity within the tubes. This contrasts to the use of 7.0 mm tubes only in previous products.

(c) Outdoor unit heat exchanger

Efforts to develop micro-channel heat exchangers and expand their application are being promoted mainly for commercial air-conditioners, with the goal of reducing the amount of refrigerant contained in each product and improving heat exchange performance.

(3) Compressor development examples

Manufacturers are designing R32 products based on proprietary technologies. Some manufacturers have developed new frictional parts and technology to recover waste heat using a heat storage material that effectively utilizes R32 discharge temperature; these companies have released products with an increased operating temperature range and improved reliability.

(4) Other

In newly released products, in addition to improving product energy-saving and comfort-enhancing performance by optimizing various element parts and control functions and incorporating sensors, manufacturers are employing technologies to improve reliability and expanding the range of operating temperature ranges to allow cooling operation under high ambient air temperatures and heating under low ambient air temperatures.

7.2.4.2.2 Use of R32 in large capacity products

Efforts are underway to promote the use of R32, starting with groups of products confirmed safe to use in risk assessments undertaken at the time of the A2L application.

(1) Case examples of the commercial introduction of multi-air conditioners for building (mini-VRF with the capacity of less than 3 tons, hybrid VRF, etc.) (Provisional)

Daikin Industries and Mitsubishi Electric sell R32 models of selected capacity class. The attached reference document provides detailed information on these products.

(2) Case examples of the commercial introduction of chillers (air-cooled type, water-cooled type)

This report introduces Daikin Industries’ module chiller as a case example. The attached reference document discusses the features of this product in detail.

7.2.4.2.3 Use of low-GWP HFO refrigerant in centrifugal refrigerating machines

As a case example, this document introduces Mitsubishi Heavy Industries Thermal Systems’ centrifugal refrigerating machine. Since the characteristics of centrifugal refrigerating machines allow the use of HFO refrigerant, the use of a refrigerant with a GWP lower than that of R32, such as HFO-1233zd(E) or HFO-1234ze(E), is being explored. The attached reference document describes the features of this product in detail.

7.2.4.3 Case examples of the commercial introduction of products that use low-GWP refrigerant (A2L) in Japan

This section introduces products with low-GWP A2L refrigerant introduced following the completion of product risk and safety assessments. As examples of such products, the following briefly describes mini-split room air-conditioners, commercial air-conditioners (light commercial split air conditioners [PAC] for store application), multi air conditioners for building (mini-VRF with capacity of less than 3 tons, hybrid VRF, etc.), chillers (air-cooled type), and centrifugal refrigerating machines.

7.2.4.3.1 <u>Case examples of room air-conditioners</u>

Almost all room air-conditioner models available in Japan are equipped with an inverter. The transition from R410A to R32 with a GWP of one-third that of R410A has been completed. The following 10 companies sell such products:

◆ Panasonic ◆ Daikin Industries ◆ Mitsubishi Electric ◆ Hitachi ◆ Toshiba

◆ Mitsubishi Heavy Industries ◆ Fujitsu General ◆ Corona ◆ Sharp ◆ Chofu

Product from Panasonic is presented below as a case example.

Panasonic Eolia X Series (CS-X220D to X900D2) released in November 2019.

(1) Product overview

Cooling capacity: 2.2 to 9.0 kW

Heating capacity: 2.5 to 10.6 kW

APF: 7.1 to 5.1

Ambient air temperature range: continuous cooling operation under 50°C possible

(2) Major technological developments

The major technologies incorporated into the heat exchanger and compressor to take advantage of the characteristics of R32 are described below.

(a) Heat exchanger

As shown in Figure 7-14 the indoor unit heat exchanger features bow-shaped, integrally molded fins with different diameter tubes arranged optimally in a limited space. Earlier heat exchangers used only 7.0 mm tubes. The diameter of the tubes in the new heat exchanger varies (5.0, 6.35, 7.0, or 7.94 mm) according to the state of the refrigerant in the heat exchanger to optimize refrigerant flow velocity within the tubes and to improve heat exchange efficiency. The new heat exchanger achieves the required heat exchange performance in about 70% of the volume capacity required for the previous heat exchanger.

(b) Recovery of exhaust heat from compressor

As shown in Figure 7-15, the high discharge temperature of R32 refrigerant, one of its characteristics, is used as a heat source. About 25% of the exhaust heat from the compressor is recovered using a heat storage material and used to melt frost accumulating on the outdoor unit. This enables the air conditioner to continue heating, even when defrosting, thereby preventing a decrease in room temperature and maintaining comfort. This approach also conserves energy. Furthermore, the compressor, a core component used for compressing the refrigerant, is a scroll compressor. Scroll compressors offer both high capacity and excellent energy-saving performance and require no accumulator. These features have been maximized to minimize the dimensions of the heat storage tank used to store recovered exhaust heat.

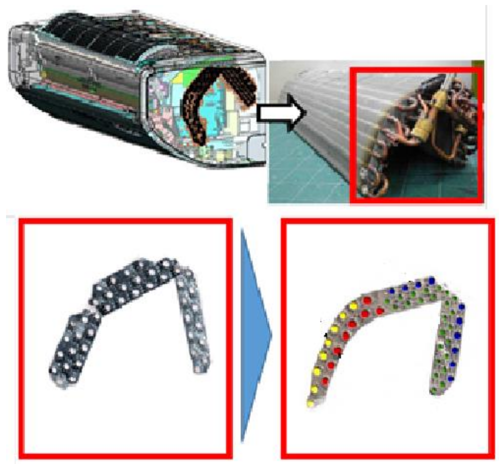


Figure 7-14: Hybrid heat exchanger in indoor unit

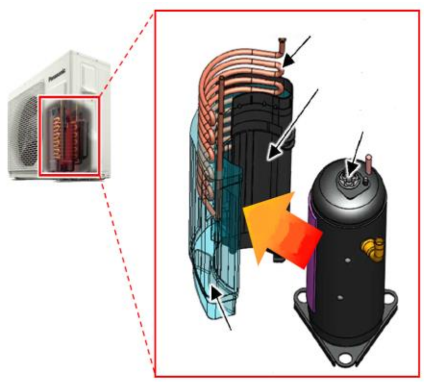


Figure 7-15: Heat recovery system

Ultra Power Eco	
	
Type P80	Types P112 to P160

Figure 7-16: External views of outdoor units

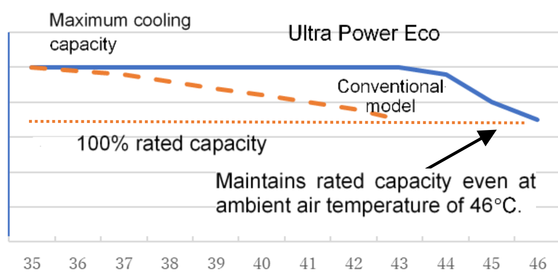


Figure 7-17: Ambient air temperature vs. cooling capacity

7.2.4.3.2 Case examples of commercial air-conditioners for commercial and office use

A shift to R32 has been promoted for commercial air-conditioners, starting with air conditioners for commercial, retail, and office spaces confirmed safe based on risk assessments, following a similar initiative for room air-conditioners. The following seven companies sell such products' brand:

◆ Daikin Industries ◆ Mitsubishi Electric ◆ Hitachi ◆ Panasonic ◆ Toshiba

◆ Mitsubishi Heavy Industries ◆ Fujitsu General

The following presents Toshiba Carrier, Johnson Controls-Hitachi and Fujitsu General's R32 air conditioning products as case examples.

Toshiba Carrier's Ultra Power Eco Series (outdoor unit: ROA-RP803HX to 1603HX):

Cooling capacity: 7.1 to 14.0 kW

Heating capacity: 8.0 to 16.0 kW

APF: 7.1 to 6.2

(1) Product overview

Expanded operating temperature range

Permissible ambient air temperatures for cooling operation: -15 to +5C°DB

Equipped with a cooling bypass circuit to reduce abnormal shutdown risks due to high temperatures. Capable of maintaining rated capacity even at ambient air temperature of 46°C.

Permissible ambient air temperatures for heating: -27 to +15C°WB.

Reduces defrosting time by 20%.

(2) Major technological developments

(a) Heat exchanger

The diameter of the heat exchanger tube has been reduced and its capacity increased, improving the heat exchange rate by about 30%.

(b) Cooling bypass circuit

The cooling bypass circuit suppresses temperature rises by diverting some of the refrigerant and using it to cool the compressor, thereby reducing compressor failures risk if ambient air temperatures rise.

(c) Compressor

The optimized compressor and high-power motor enable 10-rps compressor operations.

• The optimized discharge port position and blade thickness minimize compression losses and frictional resistance.

• Rotor improvements, including use of magnets, achieve high output, high efficiency, and low noise.

• The structural parts of the compressor are DLC-coated for improved resistance against wear.

Hitachi-Johnson Controls Air Conditioning "SHOENE NO TATSUJIN Premium" Series (Outdoor Unit: RAS-GP40RGH – RAS-GP160RGH):

Cooling capacity: 3.6-14.0 kW,

Heating capacity: 4.0-16.0 kW,

APF 7.0-6.5

(1) Product overview

Achieved energy savings by redesigning the compressor structure and the refrigeration cycle control for R32 refrigerant as well as efficiency improvement by reducing loss in ventilation path to Indoor Unit and enhancing heat exchange efficiency of the heat transfer tubes and fins.

(2) Major technological developments

Compressor

Efficiency improvement by optimized design of the displacement volume to suite R32 refrigerant characteristics and to balance out both at partial load operation with long operating time and rated load operation in APF condition.

Efficiency improvement by enhancing the sealing performance between the compression chambers and newly developing oil supply structure into the compression chamber to prevent compression leakage inside the scroll during the compression process because R32 refrigerant has a smaller molecular weight than conventional R410A refrigerant.

Figure 7-18: Outdoor unit exterior and main indoor unit exterior

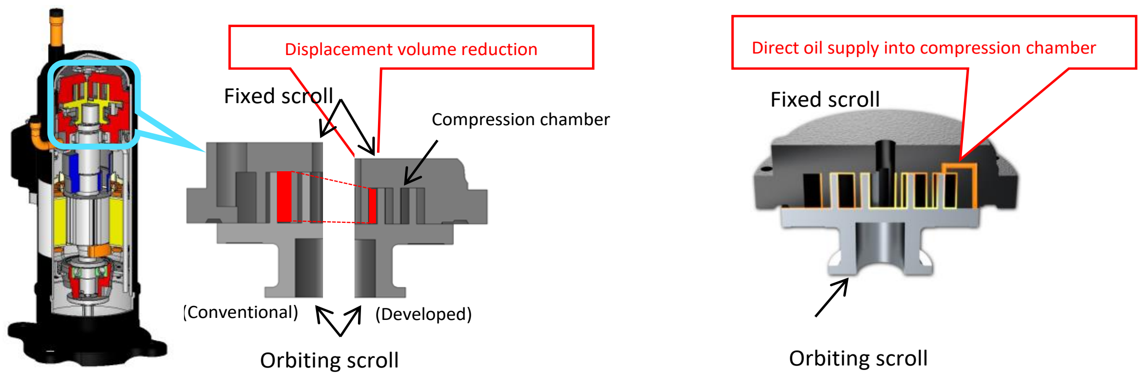


Figure 7-19: Improvements in compressors

Fujitsu General's lineup of room air-conditioners and air conditioners for commercial and office use:

All manufacturers offer a comprehensive product lineup. Shown below is Fujitsu General's lineup of R32 products (Figure 7-20).

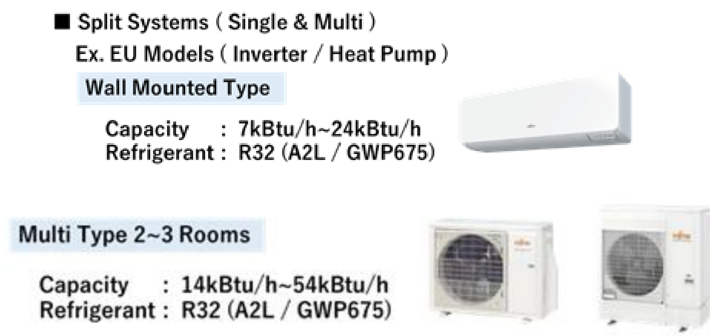


Figure 7-20: Outdoor unit exterior and main indoor unit exterior

Figure 7-21: Reduction of outdoor unit weight

Figure 7-22: Compressor

(1) Product overview

High efficiency & small and light weight outdoor unit

Outdoor unit is much more compact than conventional outdoor unit. It can be installed in a smaller place. (Figure 7-21)

(2) Major technological developments

Core components like the compressor, inverter, and propeller fan have been newly developed to suit the characteristics of R32 and to achieve high efficiency.

Compressor (Outdoor unit, Figure 7-22)

The adoption of a new-type compressor motor and a review of compressed gas passages have led to the development of a high efficiency compressor optimized for R32 (which also contributes to reduced operating noise).

7.2.4.3.3 Case examples of commercial multi air conditioners

Multi air conditioners that use R32 and have been confirmed safe by risk assessments are now commercially available. The following describes as case examples Daikin Industries and Mitsubishi Electric’s R32 products.

Daikin Industries’ individually controllable commercial multi air conditioning systems (Green Multi):

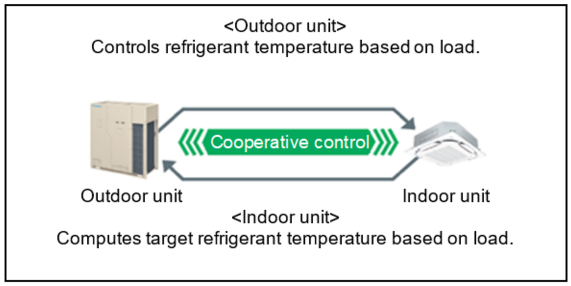


Figure 7-23: Overview of refrigerant temperature control

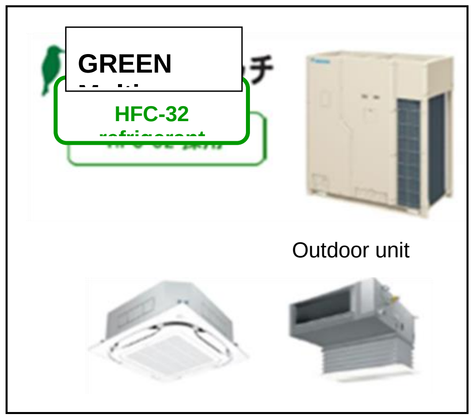


Figure 7-24: External view

(1) Product overview

GREEN Multi Series (RXUA224/280A), Released in August 2018

8-HP model: APF (2015) 6.7, 10-HP model: APF (2015) 6.4

Allowable operating temperature range

Ambient air temperature during cooling operation: -5 to +50°CDB

Ambient air temperature during heating operation: -20 to +16°CWB

Indoor unit type: Ceiling-mounted cassette type, duct type

For this product series, Daikin Industries developed a new scroll compressor and heat exchanger to allow the use of R32. An overview of those components is provided in a later section.

The use of R32 and Daikin's original all-aluminum microchannel heat exchanger reduces the amount of refrigerant required. Compared to previous models,[*1] the new product requires 25%[*2] less refrigerant and reduces the refrigerant's global warming impact by 76%[*2]. These figures meet the reduction target to be achieved by 2029[*3] as per the Kigali amendment. The product also offers high energy-saving performance to reduce CO_2 emissions during equipment operations, thereby reducing environmental load.

(2) Major technological developments

The following briefly describes the major core technologies used to develop the compressor and heat exchanger for the Daikin individually controllable commercial multi air conditioning systems that use R32.

(a) Refrigerant temperature control

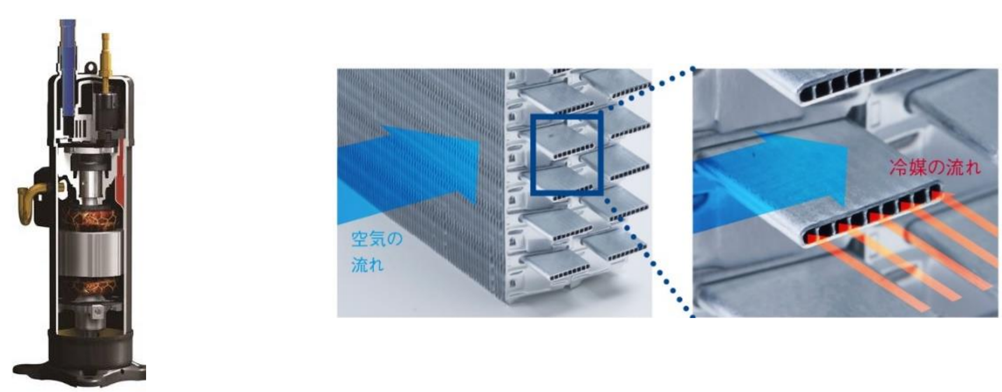
The product features an original refrigerant control technology to enable accurate control of temperature based on room loads. Figure 7-23 shows an overview of this refrigerant temperature control. The refrigerant temperature control provided in this product prevents excessive indoor cooling/heating, thereby minimizing power consumption. This ensures high energy-saving performance to reduce power consumption and CO_2 emissions, decreasing not just the adverse effects of refrigerant on global warming, but environmental loads resulting from equipment operation.

(b) Compressor

The product incorporates a newly developed scroll compressor with an R32 injection mechanism (Figure 7-25 (a)). The compressor can be installed in products with a capacity of 8 HP or 10 HP. The compressor is a variable scroll compressor incorporating an inverter with an injection mechanism to handle high R32 discharge temperatures.

(c) Heat exchanger

For this product series, Daikin developed an original all-aluminum microchannel heat exchanger, shown in Figure 7-25 (b). The microchannel heat exchanger features a design consisting of many flat small-diameter refrigerant passages. It is mounted in the outdoor unit. Since the refrigerant tube is flat, air flows smoothly around the heat exchanger tubes for efficient exchange of heat between the refrigerant and air. The microchannel heat exchanger is structured to make the best use of the high energy efficiency of R32 refrigerant. It also achieves efficient heat exchange between the refrigerant and air, reducing refrigerant amounts.



(a) Variable scroll compressor

(b) Micro-channel heat exchanger

Figure 7-25: Overview of element technologies incorporated into individually controllable commercial multi air conditioning systems using R32

Explanatory notes for *1 to *3 in the above section

*1: Compared to the average value for the high efficiency series (multi air conditioners for building) of individually controllable commercial multi air conditioning systems sold by Daikin Industries from 2011 to 2013

*2: 10-HP-equivalent systems installed using 50 m main pipe and 20 m branch pipe

*3: Phased reduction of 70% by 2029 from the reference value determined based on the average quantity of HFC production/consumption in the period from 2011 to 2013 in industrialized nations, including Japan

Mitsubishi Electric's R32-Hybrid VRF commercial air-conditioner:

The following is an excerpt from a technical paper on Mitsubishi Electric's R32-Hybrid VRF.

(1) Overview of R32-Hybrid VRF (Nominal 22.4 – 56 kW cooling / 25 – 58 kW heating)

The environment-friendly R32-Hybrid VRF configuration combines the advantages of R32 refrigerant, whose global warming potential (GWP) is about one-third that of R410A refrigerant, and the advantages of the Hybrid VRF, which achieves reductions in refrigerant amounts by transferring heat via water from the Hybrid Branch Controller to the indoor unit. It is the world's first system that uses mildly flammable R32 refrigerant for multi air conditioning systems with two-pipe heat recovery functions and individually controlled indoor units and yet requires no safety measures, even when indoor units are installed in a small room.

Figure 7-26 shows a Hybrid VRF system. Hybrid VRF is comprised of an outdoor unit; a Branch Controller; and a plurality of indoor units, similar to a conventional VRF with heat recovery functions. A pair of pipes connects the outdoor unit to the Branch Controller and the Branch Controller to the indoor unit. While the VRF transports heat between the outdoor unit and the indoor unit via the refrigerant, the Hybrid VRF transports heat between the outdoor unit and the Hybrid Branch Controller (mainly outdoors) via the refrigerant and between the Hybrid Branch Controller and indoor units (indoors) via water.

Hybrid VRF connects two refrigerant pipes from the outdoor unit to the Hybrid Branch Controller to enable simultaneous cooling and heating. This generates cold water and hot water at the same time for the indoor unit. Since the Hybrid VRF is a package system that includes valves, pumps, and heat exchangers in the Hybrid Branch Controller, it has fewer components than four-pipe chiller systems, simplifying system design. Moreover, since the Hybrid VRF is a two-pipe system, it features fewer piping connections than a 3-pipe VRF system.

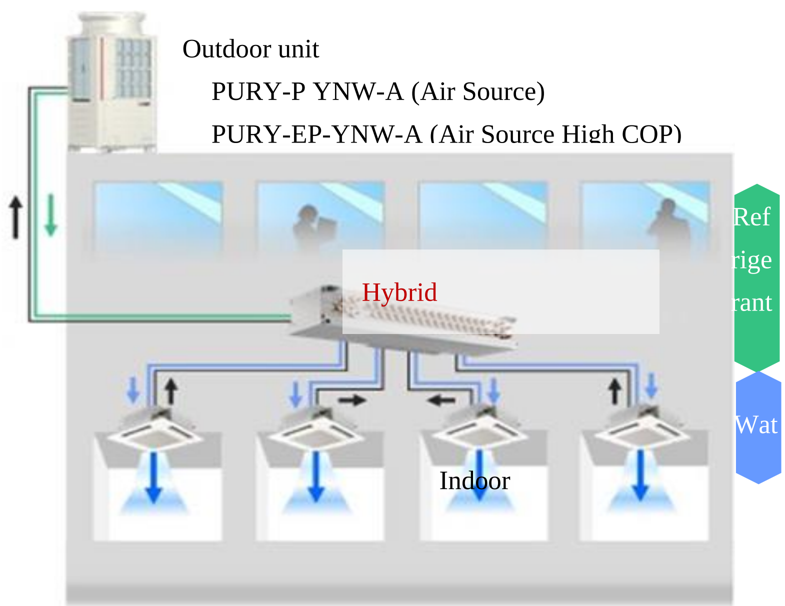


Figure 7-26: Hybrid VRF

The R32-Hybrid VRF transfers heat from the Hybrid Branch Controller to the indoor unit via water. In this way, the Hybrid VRF can eliminate the use of refrigerant from the Hybrid Branch Controller to the indoor unit and reduce the volume of refrigerant needed. In the case of a hotel operating multi air conditioner with rated cooling capacity of 33.6 kW and 2.2 kW × 20 indoor units, the R32-Hybrid VRF can reduce refrigerant volumes by 52 percent compared to the R410A-VRF and reduce greenhouse gas emissions (CO_2 equivalent) by 84 percent (in this calculation, the refrigerant pipe lengths of VRF and R32-Hybrid VRF are 264 m and 40 m, respectively; in each case, the refrigerant piping length from the outdoor unit of the VRF and the R32-Hybrid VRF to the Branch Controller is 40 m).

The R32-Hybrid VRF transfers heat from the Hybrid Branch Controller to the indoor unit with water to restrict the area through which the refrigerant flows. Installing the Hybrid Branch Controller above the ceiling in the upper part of the room makes it possible to prevent direct refrigerant leakage indoors, especially in small spaces. No safety measures are required, even in cases involving the mildly flammable R32 refrigerant.

(2) Elemental Technology for Configuring Equipment Systems

(a) Hybrid Branch Controller

Figure 7-27 shows the Hybrid Branch Controller ("HBC" hereafter). The HBC consists of valve blocks, two plate heat exchangers, and two pumps. The plate heat exchanger exchanges heat between the refrigerant supplied from the outdoor unit and water flowing from the indoor unit. The low-profile plate heat exchangers are used to install the HBC above the ceiling. The valve block switches the path of flow of water circulating between the HBC and the indoor unit and controls water flow rates. The pump circulates water between HBC and the indoor unit. Water flowing from the pump exchanges heat at the plate heat exchanger and is cooled or heated. Cold/hot water flowing from the plate heat exchanger is distributed to each indoor unit by the valve blocks, which exchange heat with air in the indoor unit. Two pumps circulate water from the indoor unit, and this water is distributed by the valve blocks.

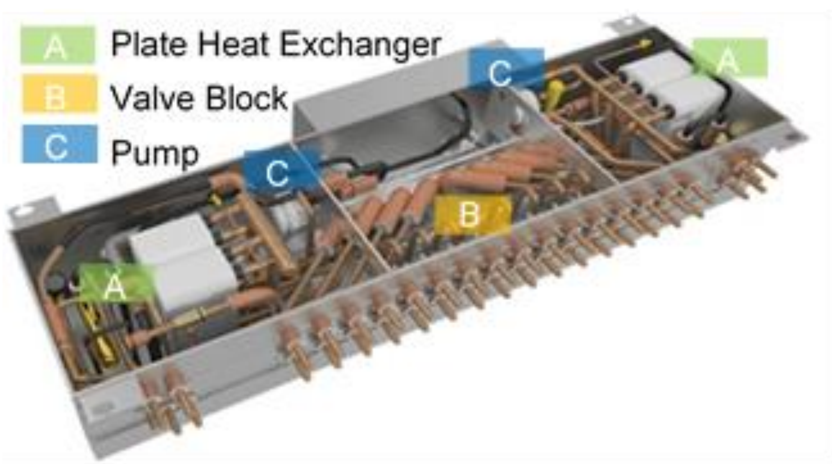


Figure 7-27: Hybrid Branch Controller

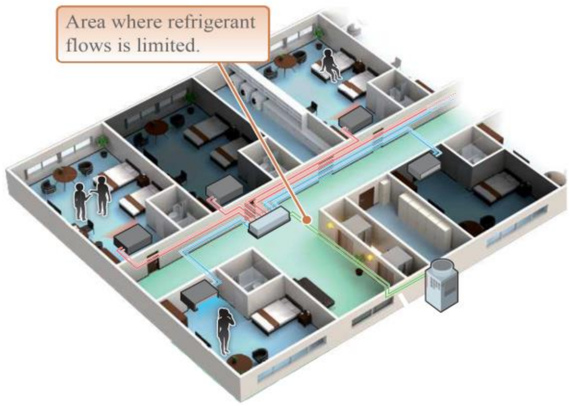


Figure 7-28: Installation image of R32-Hybrid VRF

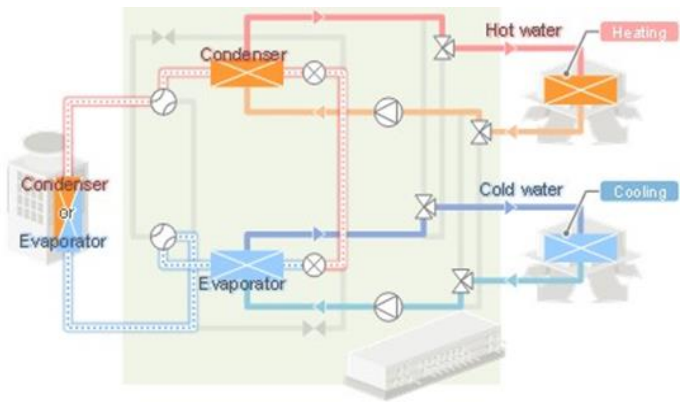


Figure 7-29: Refrigerant and water circuit diagram in heating and cooling operation mode

(b) Operating Modes

For heating, two plate heat exchangers act as condensers and generate the hot water needed to heat the room. Water circulating in the heating indoor unit takes up heat from the high temperature and high pressure gas refrigerant at the plate heat exchanger; is heated to become hot water; and is supplied to the indoor unit. For the cooling operation, two plate heat exchangers serve as evaporators to generate the cold water required to cool the room. Water circulating in the indoor unit to be cooled gives up heat to the low temperature, low pressure two-phase refrigerant at the plate heat exchanger until the water is cold, and is then supplied to the indoor unit. Figure 7-29 shows how the refrigerant circuit and water circuit function during simultaneous cooling and heating. Two plate heat exchangers act as condensers and evaporators to generate the hot and cold water needed to cool or heat the room. The water circulating in the heating indoor unit takes on heat from the high temperature and high pressure gas refrigerant at a plate heat exchanger that functions as a condenser and is heated and supplied to the indoor unit. The refrigerant condensed and liquefied in the condenser passes through the expansion valve, then becomes a low temperature, low pressure two-phase refrigerant. Thereafter, it flows into the plate heat exchanger functioning as an evaporator. The water circulating in the indoor unit to be cooled gives up beat to the low temperature, low pressure two-phase refrigerant at a plate heat exchanger and is cooled and supplied to the indoor unit.

(c) Prevent refrigerant leakage into the room

In the R32-Hybrid VRF (Figure 7-28), the HBC is installed above the ceiling. Indoor units with water circulation are installed in each room, preventing direct refrigerant leaks into the space, especially small spaces. Thus, even if the entire volume of the refrigerant leaks, the refrigerant concentration in each room will not exceed the specified concentration. No safety measures are required, even when using mildly flammable R32.

7.2.4.3.4 <u>Case examples of commercial introduction of chillers (air-cooled type)</u>

The shift to R32 is also being promoted for chiller systems. As a case example, the following introduces a product from Daikin Industries.

Daikin Industries' HEXAGON Force 32: (Released in November 2018)

Figure 7-30: External view of HEXAGON Force 32 (4 units connected)

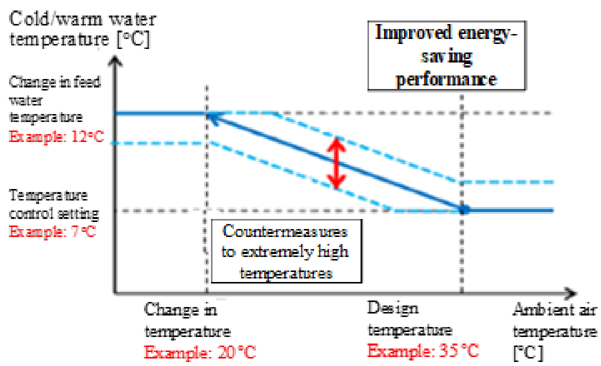


Figure 7-31: Overview of variable feed water temperature control

(1) Product overview

HEXAGON Force 32 (HEXAGON Force)

Capacity class: 30 to 60 HP (UWXY85FA, 118FA, 150FA, 180FA)

Daikin's HEXAGON Force 32 (HEXAGON Force) is the first[*1] central air conditioning system to use a low-GWP R32 refrigerant. It boasts industry-leading energy-saving performance. The air-cooled heat-pump module chiller models were launched in succession from November 2018. This product series includes R32 models with capacities ranging from 30 to 60 HP. Figure 7-30 shows the HEXAGON Force 32 air-cooled heat-pump module chiller that uses R32. For this product, Daikin developed an R32 scroll compressor. An overview of the compressor is provided in a later section.

Using R32, whose GWP is one-third of R410A, this product reduces global warming effects by 68%*2 compared to conventional products.

The scroll compressors in this product series are equipped with an intermediate injection circuit that maximizes R32 heating performance. This improves heating performance by 5% in models of all classes compared to conventional products*3 and achieves industry-leading*4 heating COP.

Explanatory notes for *1 to *4 in the above section

*1: As of June 2018, according to Daikin Industries' survey

*2: Refrigerant effects on global warming, calculated by multiplying global warming potential (GWP) by amount of refrigerant. The GWP value used is the 100-year value specified in the IPCC Fourth Assessment Report.

*3: HEXAGON Force module chillers UWXY-F and UWXA-F (R410A models)

*4: Operating efficiency during periods when high loads are applied to air conditioners, such as midsummer and midwinter.

Daikin Industries also sought to maximize user convenience, equipping the product as part of the standard configuration with an inverter pump that regulates the amount of water to reduce power consumption and with an active filter that suppresses higher harmonics to minimize adverse effects on other equipment. The product is easy to install and offers improved functionality.

To further improve energy-saving performance and ease of use. Daikin developed a variable feed water temperature control, available as an option in the new BRG305A series module controllers. Figure 7-31 gives an overview of this control.

The variable feed water temperature control provided in the product ensures high energy-saving performance and sufficient cooling, even on extremely hot days. It prevents excessive cooling/heating of the room, minimizing power consumption.

Specifically, the control function features not just a conventional operation efficiency priority control that automatically adjusts equipment operations to maintain the most efficient operating conditions at all times, but a variable feed water temperature control as an option for the new BRG305A series module controller to further improve both energy-saving performance in actual use and user convenience. This function controls cold/warm water temperatures based on indoor environmental loads to prevent excessive cooling/heating of the room, thereby reducing power consumption.

(2) Major technological developments

(a) Compressor

Daikin Industries has developed a scroll compressor with an R32 injection mechanism. This compressor is a variable scroll compressor that uses an inverter with an injection mechanism to handle the high discharge temperature of R32.

Figure 7-32: Variable scroll compressor

7.2.4.3.5 Case examples of commercial introduction of centrifugal refrigerating machines that use HFO refrigerant

The use of R32 as a low-GWP refrigerant has expanded to many products, as described up to this point. The use of HFO refrigerants has also begun in centrifugal refrigerating machines. The following introduces Mitsubishi Heavy Industries Thermal Systems' products as case examples.

Figure 7-33: Appearance of ETI-Z series

Figure 7-34: Appearance of GART-ZE/ZEI series

(1) Product overview

- ETI-Z series

    - Refrigerant: HFO-1233zd(E)
    - Released in September 2015
- GART-ZE/ZEI series
    - Refrigerant: HFO-1234ze(E)
    - Released in April 2017
    - Refrigeration capacity range: 150 to 5,000 USRt

(2) Product lineup

The product lineup includes the small-capacity ETI-Z series and large-capacity GART-ZE/ZEI series, covering a range of refrigeration capacity from 150 to 5,000 USRt. Table 7-40 presents the major specifications for this product series. Figure 7-33 and Figure 7-34 show external views.

Table 7-40: Main specifications of ETI-Z and GART-ZE/ZEI series

	ETI-Z series	*GART-ZE/ZEI series*
Refrigerant	HFO-1233zd(E)	HFO-1234ze(E)
Capacity range	150-700 [USRt]	300-5,000 [USRt]
Max. Rated COP*1	6.3	6.4
Max. COP at part load*2	25.5	24.0 (Valuable control)
Maximum IPLV (JIS condition)	9.1	7.2 (Fixed control) 8.8 (Valuable control)

*1 JIS condition. (Chilled water temperature 12/7°C, Cooling water temperature 32/37°C)

*2 Chilled water outlet temperature 7°C, Cooling water input temperature 12°C

(a) ETI-Z series

Using HFO-1233zd(E) with a GWP of 1, this series of models equipped with a single compressor cover the capacity range of 150 to 350 USRt. The models with two compressors provide capacities of up to 700 USRt. The rated COP is 6.3, and the IPLV value, which indicates partial load performance, is 9.1; the products are compact and yet offer high performance. Furthermore, since the heat exchanger is integrated with a 400 V-class inverter, the products are easy to install.

(b) GART-ZE/ZEI series

The GART-ZE/ZEI series uses HFO-1234ze(E) with a GWP of less than 1. The models equipped with a single compressor cover the range from 300 to 2,500 USRt. Models with two compressors provide capacities of up to 5,000 USRt. The GART-ZE series are standard constant-speed models. The GART-ZEI series are variable-speed models. These series can be used not just for cooling and heating rooms, but for heat recovery, heat pump, and low temperature heat storage applications. The compound models with two compressors connected in series can be used for process cooling applications to reduce temperatures to -20°C or below and for heat pump applications in which a heating tower temperature of lower than -10°C is used as a heat source.

(3) Major technological developments

The specific volume of the HFO-1233zd(E) gas used in the ETI-Z series is about five times that of HFC-134a. The specific volume of HFG-1234ze(E) used in the GART-ZE/ZEI series is about 1.3

times that of HFC-134a. If a system were designed in the same way as a system using the previous refrigerant, the capacities of the compressor, evaporator, condenser, gas pipe, and others in the refrigerant gas passages would need to be increased. However, the following design improvements and engineering efforts improve performance, reducing installation space and special volumes to the same as or less than those for the previous product to facilitate use of the products as replacement units.

(a) Adoption of aerodynamically designed shape suitable for each refrigerant type

The shape of the compressor has been aerodynamically designed to provide greater air flow than conventional compressors of the same-diameter blades to handle the increased specific volumes of the refrigerant gas. Since the increase in the design air flow rate tends to reduce insulation efficiency, the shapes of the impeller blades and suction vanes were optimized through CFD analysis (Figure 7-35), increasing insulation efficiency and air flow rate by 3% and 60%, respectively, compared to a unit of the same capacity, and allowing use of a smaller compressor.

(b) Direct coupling of compressor and motor (ETI-Z series)

The impellers are connected directly to the motor shaft because the increased specific volume of the refrigerant would decrease the rotation speed of the compressor if the refrigeration capacity were the same. This enables the compact compressor to rotate at high speed and reduces the number of compressor bearings and step-up gears, reducing pressures losses and improving reliability. The arrangement of the impellers and motor on the same axis also contributes to small compressor size.

(c) High performance technology for the heat exchanger

The heat exchanger is a shell-and-tube type. Since the specific volume of the refrigerant gas is significant and the pressure difference between the condenser and evaporator is small compared to that in a conventional unit, each component is optimally positioned to suppress caused by refrigerant flow. Special design attention was given to minimizing dry-out, which is caused by local increases in the amount of refrigerant in the evaporator and reduces the heat exchange performance of the heat transfer tube. This keeps refrigerant liquid droplets from being drawn into the compressor with refrigerant gas from the upper section of the heat transfer tubes and minimizes pressure losses in the region where refrigerant gas flows into the condenser.

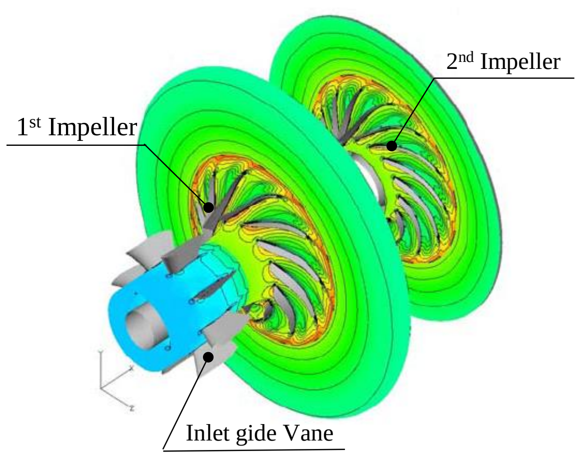


Figure 7-35: CFD analysis of compressor

7.3 LCCP Evaluation for Air-to-air Heat Pumps using Next-generation Refrigerants (Report 1: first step) Residential Air Conditioners

Prepared by

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7.3.1 Summary

In Japan, a two-step process is applied to the LCCP evaluation of heat pump-type air conditioners with next-generation refrigerants. This report mainly describes the first step of the process through to the LCCP evaluation methods, together with the concept of the study utilizing field data and hypotheses.

In particular, a representative model is selected as an example of general split-type air conditioners, and it is considered in two ways, one of which is only as evaluation for a system drop-in of candidate refrigerants replacement while the other is in terms of system optimization, both using the candidate refrigerants to be examined R290, R32, R454C (and R22, R410A). Based on such systems, this report explains a calculation method using the performance simulation that is adopted as a standard tool by the Japan Refrigeration and Air Conditioning Industry Association (hereinafter referred to as “JRAIA”).

The report also presents an overview of a project to establish a new concept and hypothesis for LCCP evaluation in which field data related to air conditioners is adopted.

7.3.2 Introduction

The main issues of recent urgent environmental efforts to address global warming in relation to air conditioners (hereinafter referred to as "A.C.") are the Kigali Amendment to the Montreal Protocol globally, the F-Gas Regulation in Europe, and the Act on Rational Use and Proper Management of Fluorocarbons in Japan.

The Kigali Amendment is a regulation aimed at gradually reducing the production and consumption amounts of refrigerants used in CO_2 equivalents. This regulation is a global warming countermeasure to be promoted worldwide by focusing on a transition to lower GWP refrigerants. For actual global warming countermeasures, it is important not only to reduce the GWP of the refrigerant but also to improve the performance of equipment by reducing the amount of greenhouse gas emissions derived from power consumption.

Figure 7-36 gives an overview of the forecast of demand for residential A.C. cooling by 2050 by country/region based on the Future of Cooling report published by the International Energy Agency (hereinafter referred to as "IEA") [1]. As can be seen, the chart indicates that the world's demand for residential A.C. cooling will expand rapidly by 2050. The use of A.C. in the United States and Japan will increase at a gradual pace. On the other hand, due to growing demand in India, Indonesia, Brazil, China, and EU countries, the world's A.C. demand is projected to rise considerably – by more than three times – by 2050.

It is anticipated that such an increase in A.C. demand will not only cause refrigerants to have a direct impact on global warming but also possibly give rise to an increase in the indirect impact on global warming due to the power consumption of A.C. equipment. Therefore, in addition to the direct impact of refrigerants, the energy efficiency and power consumption of equipment will become the focus of even greater attention in the years to come.

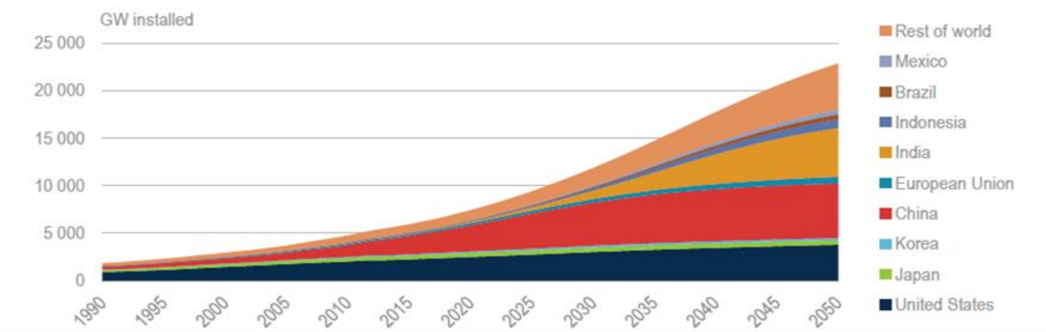


Figure 7-36: Residential AC cooling capacity in the baseline scenario by country/region

For this reason, we believe the LCCP evaluation to be studied in Task 3 is an important evaluation for selecting the most suitable refrigerants because it considers the transition to lower GWP refrigerants and the environmental impact of power consumption. To make the evaluation more realistic, based on the concept of S+3E (Safety, Environment Performance, Energy Efficiency, Economic Feasibility) advocated by JRAIA, it is desirable to conduct a comprehensive evaluation from multiple perspectives, including safety, cost, sustainability, and infrastructure development, in addition to environmental assessment through the LCCP evaluation.

The study conducted by JRAIA in December 2008 [2] is introduced as a previous case study relating to the LCCP evaluation. The LCCP evaluation, in this case, was based on a simplified simulation, with climate and other conditions set in accordance with Japanese Industrial Standards (hereinafter referred to as "JIS").

There is also a case study concerning IEA-related LCCP evaluation, which was presented by the University of Maryland in the United States (hereinafter referred to as “UMD”) [3]. In this paper, mainstream residential air-conditioners (ACs) in the United States are evaluated; therefore, it is necessary to conduct an evaluation for the split-type heat pump ACs that are in conventional residential use in Japan and Asia.

Accordingly, in Japan, a new LCCP evaluation is carried out in two steps for heat pump-type ACs that use next-generation refrigerants. The first step (this report) examines the LCCP evaluation methods, and the second step, which will be implemented in the future, will mainly describe a new evaluation that applies performance simulation and the concept and hypothesis of the study utilizing market data.

In the evaluation in this report, a representative model of typical split-type ACs is selected, and refrigerants R290, R32, R454C, R22, and R410A are examined. Since the indirect impact of power consumption varies significantly depending on the market and factors such as climate conditions and lifestyle, the first step evaluates this under the standard conditions in Japan. The performance evaluation method verified jointly by JRAIA and Waseda University is used. As the second step, evaluation will be conducted based on the possibility of the application of actual market data that varies according to local climate conditions, and Report 2 will explain the established concept and hypothesis about this approach.

7.3.3 Concept of LCCP Evaluation

This chapter explains the concept of the LCCP evaluation.

Basically, the calculations of LCCP are carried out in accordance with the guidelines published by the International Institute of Refrigeration (hereinafter referred to as “IIR”) [4]. The components to be evaluated for LCCP are shown in Figure 7-37.

This chapter describes how to calculate the amount of refrigerant charge and annual energy consumption.

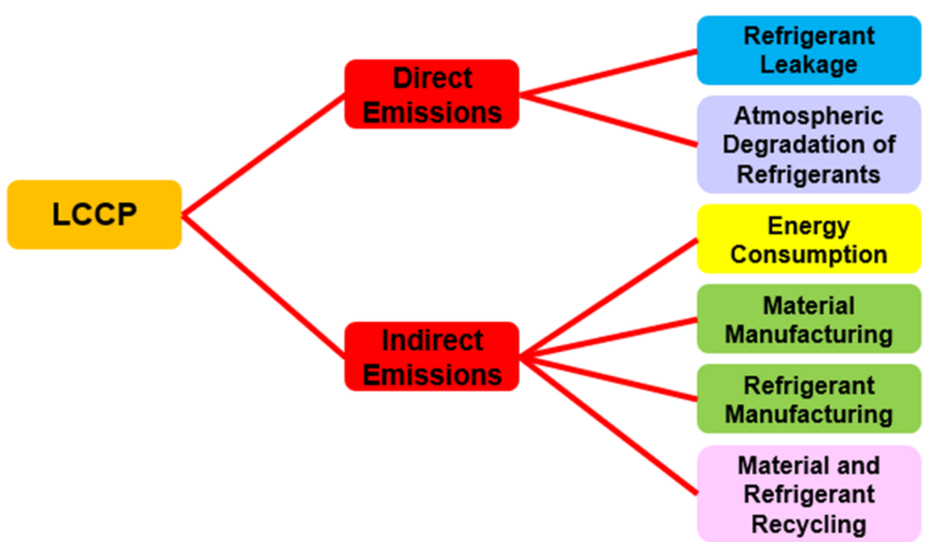


Figure 7-37: LCCP components

7.3.3.1 Concept of Candidate Refrigerants

This section explains the concept of candidate refrigerants for examination in the LCCP evaluation in this project.

The candidate refrigerants include R410A, a pseudo-azeotropic refrigerant mixture of an HFC refrigerant, and R32, an HFC single refrigerant, both of which are used in current A.C. units. In addition, R454C was selected as a zeotropic mixture of HFO and HFC refrigerant with a relatively large temperature glide, which is attracting attention as a low-GWP refrigerant. We also selected the natural refrigerant R290, which has a lower operating pressure than R410A and R32, and the HCFC refrigerant R22, which is still adopted in many current ACs in emerging nations and is an important refrigerant for comparison with R290.

Table 7-41 shows the properties of each refrigerant [5] and Table 7-42 shows the theoretical COP calculated based on the thermodynamic properties of the refrigerants.

As described above, five refrigerants were selected for the study from the perspective of comprehensively covering the properties of the next-generation refrigerants in relation to system performance: R410A, R32, R454C, R290, and R22.

Table 7-41: Comparison of refrigerant properties

	R410A	R32	R454C	R290	R22
Composition	R32/R125 (50/50 wt%)	Pure fluid	R32/R1234yf (21.5/78.5 wt%)	Pure fluid	Pure fluid
GWP	2090	675	148	3	1810
Safety Label	A1	A2L	A2L	A3	A1

Table 7-42: Comparison of theoretical COP

		Cooling					Heating				
		R410A	R32	R454C	R290	R22	R410A	R32	R454C	R290	R22
Evaporating Pressure	MPa	1.087	1.107	0.591	0.637	0.681	0.799	0.813	0.432	0.474	0.498
Condensing Pressure	MPa	3.067	3.141	1.691	1.713	1.943	2.142	2.190	1.177	1.218	1.355
Temperature glide	K	0.1	0.0	5.6	0.0	0.0	0.1	0.0	6.2	0.0	0.0
Suction Temperature	℃	15.1	15.0	18.5	15.0	15.0	5.1	5.0	8.7	5.0	5.0
Discharge Temperature	℃	71.6	84.3	59.4	58.5	71.7	55.4	67.7	44.5	43.8	56.1
Theoretical COP	-	5.49	5.63	6.02	5.88	5.94	6.72	6.58	7.93	7.61	7.27
Volume Capacity	kJ/m^3	6,404	7,045	3,700	3,737	4,456	5,516	5,749	3,450	3,478	3,826

*Condensing temperature Cooling50/Heating35℃,

Evaporation temperature Cooling10/Heating0℃,

Suction superheat 5K, Sub-cooling 10K

Saturation temperature of zeotropic refrigerants is midpoint temperature of two -phase region under constant pressure.

7.3.3.2 Examined A.C. and Performance Simulation

The A.C. to be examined is a split-type heat pump A.C. Widely distributed ACs are diverse according to the manufacturer and development year; therefore, in this project, we decided to examine a residential A.C. for which JRAIA defined the standard specifications.

More specifically, the selected A.C. is equivalent to a high-end unit, and an analysis model (standard model) with a rated cooling capacity of 4 kW was created for the examination. An overview of the ACs' refrigerant circuits is shown in Figure 7-38.

The performance simulation was conducted using the simulation software Energy Flow +M, which was developed by Professor Saito's Laboratory at Waseda University and is used by JRAIA as a standard tool. Figure 7-389 shows the refrigerant circuit diagram of the standard model constructed with this performance simulation software.

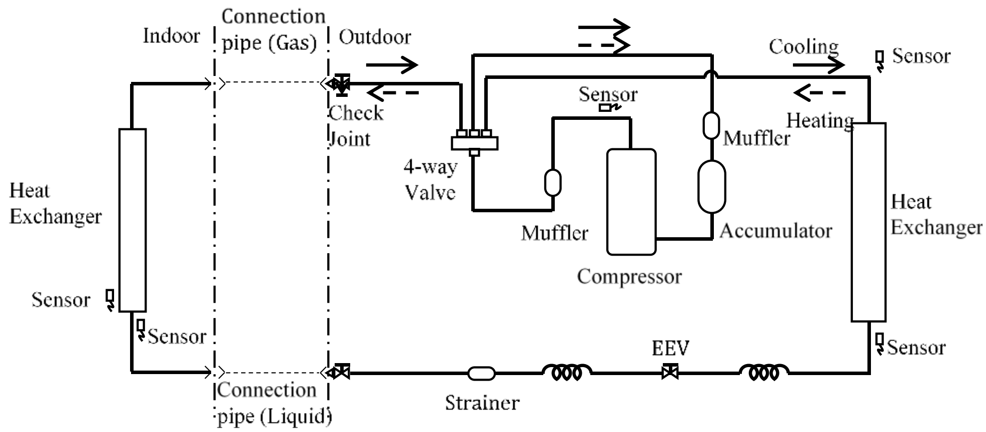


Figure 7-38: Refrigerant circuits for split type air conditioner

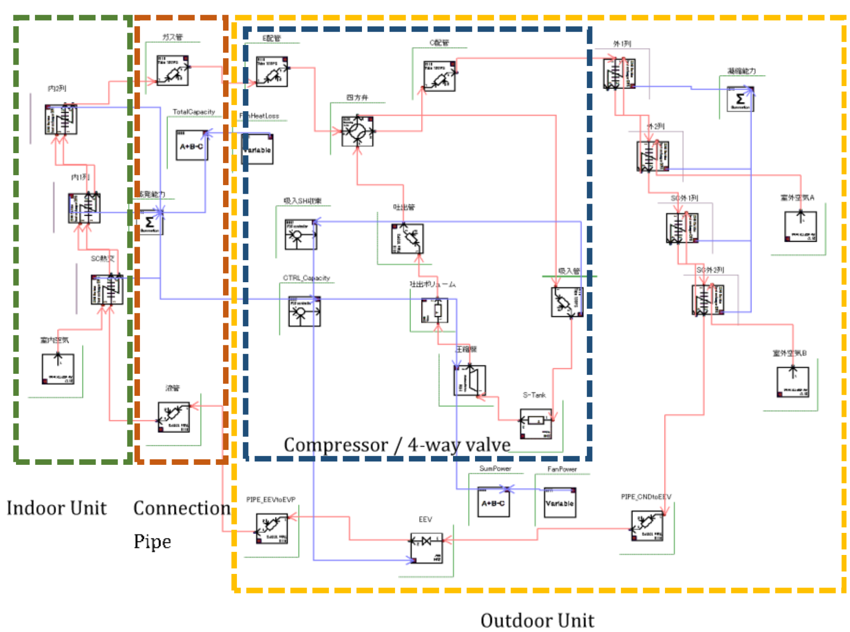


Figure 7-39: Project layout for standard model

To examine this standard model with greater accuracy, a comparative verification was made between the performance simulation results and the actual equipment test results for the case where the R410A was used for operation. Table 7-43 shows a comparison with the actual equipment test results. To implement more advanced performance simulation, each element device consisting of the refrigeration cycle was calibrated so that both the capacity and power input in Table 7-43 have an accuracy of ±10%.

Table 7-43: Calibration results of standard model

		Cooling		Heating	
		Actual	Calculated	Actual	Calculated
Capacity	%	100	95	100	99
Power consumption	%	100	111	100	102

7.3.3.3 Performance Simulation Conditions

This section describes the calculation conditions for performance simulation shown in Table 7-44.

The performance test conditions for ACs have been evaluated by means of JIS C 9612 (2013). Its performance evaluation method is carried out through a relative comparison under the predetermined conditions for the balance point (condensation and evaporation temperatures, suction superheating degree, and subcooling degree), which is the operating status point.

A.C. performance is evaluated by calculating an Annual Performance Factor (hereinafter referred to as “APF”). To calculate the APF, operation modes are set for each of cooling and heating, and the capacity is set for each of the test conditions and a Coefficient of Performance (hereinafter referred to as “COP”) is calculated. A.C. performance is evaluated based on a relative comparison using the APF.

These evaluations are conducted for each case of using a single refrigerant and using an azeotropic (including pseudo-azeotropic) refrigerant mixture, and for the latter, performance is evaluated using a technique called the “cycle midpoint protocol (boiling point/dew point)” as specified in JIS B 8623 (2019), which defines condensation and evaporation temperatures.

In addition, the expansion valve opening degree is adjusted so that the suction superheating degree (= compressor suction gas temperature – saturation temperature in compressor suction gas) is 5°C, and performance is evaluated using the same methods described above. Regarding the subcooling degree, the amount of refrigerant charge is adjusted so that the maximum COP is achieved for each refrigerant.

Table 7-44: Calculation conditions

TEST		Cooling	Heating
Air Entering of Indoor unit	Dry Bulb[°C]	27.0	20.0
	Wet Bulb[°C]	19.0	15.0
Air Entering of Outdoor unit	Dry Bulb[°C]	35.0	7.0
	Wet Bulb[°C]	24.0	6.0
Cycle Point	Capacity	Same at each operation point	
	SH	5.0 K at Suction Temperature	
	SC	At Optimum Performance	

7.3.3.4 Calculation of LCCP

Basically, LCCP is calculated in accordance with the guidelines published by the IIR.

The calculation methods for refrigerant charge, annual energy consumption, and other items are arranged and implemented as follows.

(1) Equipment: JRAIA AC standard model (H/P split type) equivalent to high-end unit with a rated cooling capacity of 4 kW

(2) Tool: JRAIA standard tool Energy Flow +M (Prof. Saito's Lab at Waseda University)

(3) Comparison: Optimization is performed for each refrigerant to calculate the amount of refrigerant charge and the annual energy consumption.

(4) Selection of refrigerant types: Five refrigerants (R410A, R32, R454C, R290, and R22) were selected based on the above-mentioned concept.

(5) Calculation conditions: As described above, the power consumption in a refrigeration cycle with the same capacity is calculated under the conditions shown in Table 7-44.

7.3.4 LCCP Evaluation Conditions and Specifications

This chapter describes the evaluation conditions and specifications for LCCP.

7.3.4.1 Definitions of LCCP Equations:

The definitions of the LCCP equations are stipulated as the LCCP evaluation conditions. LCCP is calculated by obtaining the sum of the direct and indirect emissions according to the method proposed by Dr. Hwang of UMD [3]. The method of calculating the direct emissions is shown in Equation 1. Indirect emissions are calculated using Equation 2. The following is a brief summary of the LCCP calculation.

$$\text{LCCP} = Direct\ Emissions + Indirect\ Emissions$$

$$Direct\ Emissions = C \times (L \times ALR + EOL) \times (\text{GWP} + Adp.\text{GWP}) \qquad \text{... Equation 1}$$

$$Indirect\ Emissions = L \times AEC \times EM + \sum(m \times MM) + \sum(mr \times RM) + C \times (1 + L \times ALR) \times RFM + C \times (1 - EOL) \times RFD \quad \text{... Equation 2}$$

The symbols in the evaluation equations are shown in Table 7-45.

Table 7-45: Symbol description

C	kg	Refrigerant Charge
L	yr	Average Lifetime of Equipment
ALR	% of Ref. Charge	Annual Leakage Rate
EOL	% of Ref. Charge	End of Life Refrigerant Leakage
GWP	$kgCO_2e/kg$	Global Warming Potential
$Adp.\ GWP$	$kgCO_2e/kg$	GWP of Atmospheric Degradation Product of the Refrigerant
AEC	kWh	Annual Energy Consumption
EM	$kgCO_2e/kWh$	CO2e Produced / kWh
m	kg	Mass of Unit
MM	$kgCO_2e/kg$	CO2e Produced / Material
mr	kg	Mass of Recycled Material
RM	$kgCO_2e/kg$	CO2e Produced / Recycled Material
RFM	$kgCO_2e/kg$	Refrigerant Manufacturing Emissions
RFD	$kgCO_2e/kg$	Refrigerant Disposal Emissions

7.3.4.2 Influential Factors of LCCP:

This section describes influential factors when calculating LCCP.

Table 7-46 summarizes the calculation items used in Equation 1 for the direct emissions and in Equation 2 for the indirect emissions in the LCCP calculation. Table 7-46 indicates that LCCP involves various influential factors. Therefore, when evaluating LCCP, it is necessary to clarify its influential factors and parameterize them for the study. There is particular concern that the evaluation may significantly differ depending on the country or region.

For example, with regard to energy conversion, since the power generation systems vary by country or region, the data that comes under Equation 1 for the direct emissions and Equation 2 for the indirect emissions are deemed to be influential factor parameters for energy conversion. By replacing these influential factor parameters as appropriate for each country or region, it is possible to estimate valid LCCP.

Table 7-46: Assumption parameters used for LCCP calculation

Symbol	unit
C	kg
L	yr
ALR	% of Ref. Charge
EOL	% of Ref. Charge
GWP	$KgCO_2e/kg$
AEC	kWh
EM	$KgCO_2e/kWh$

7.3.4.3 Evaluation Applying Performance Simulation:

To predict the performance of A.C. equipment, which will have a major impact on the LCCP evaluation, a newly constructed performance simulation with improved prediction accuracy is used in the study.

Figure 7-39 shows the schematic configuration of the standard model used for performance simulation in this study. The standard model was created based on the specifications of a common commercially available heat pump A.C.

In this study, to take into account the design concept for actual ACs, the performance is predicted assuming drop-in (hereinafter referred to as “DI”) and soft optimization (hereinafter referred to as “SO”) in the performance simulation. Specifications optimized with greater awareness of A.C. product capabilities (e.g., size equivalence and energy efficiency equivalence) are also examined. The DI evaluation in this study refers to performance evaluation where the same A.C. equipment is used but only the refrigerant is replaced. However, regarding equipment mounted with an inverter compressor and electronic expansion valve, the compressor frequency is changed (change of refrigerant mass flow rate) with the same A.C. capacity, and the expansion valve opening degree is changed with the same suction superheating degree. In addition, the SO evaluation refers to performance evaluation with minor modifications added on the A.C.’s hardware, such as changing the diameter of the connection pipe so that almost the same pressure drop occurs in the circuit even when different refrigerants are applied. Table 7-47 shows the concept of the assumed specification changes.

As shown in Table 7-47, compared with the base A.C. (a), in (b) the charged refrigerant (R410A) was changed, the refrigerant amount was adjusted to equalize the subcooling degree, and the compressor frequency was also changed to equalize the capacity before comparison. In (c), for the connection pipes of the liquid side and gas side that connect the indoor and outdoor units, the pipe diameter was optimized so that the pressure drop is equal to that of the current refrigerant. In (d), while maintaining the size of the heat exchanger, the path was changed to achieve the maximum efficiency. In (e), the size of the heat exchanger was changed to equalize the energy efficiency.

The refrigerant used for the base model is R410A.

Based on these studies, the values for the refrigerant charge amount, C, and the annual energy consumption, AEC, which are factors affecting the LCCP evaluation, are calculated, and a comparative assessment is made using the obtained values.

Table 7-47: Specification of refrigeration cycle

		(a)	(b)	(c)	(d)	(e)
		Base model	Drop in	Soft optimization	Optimization (Same size)	Optimization (Same efficiency)
Outdoor unit	Row	2	←	←	←	Optimize
	Column	35	←	←	←	Optimize
	Cooling path	6-3-1	←	←	Optimize	Optimize
Indoor Unit	Row	3	←	←	←	Optimize
	Column	21	←	←	←	Optimize
	Cooling path	1-3	←	←	Optimize	Optimize
Connection pipes	Liquid	Φ6.35	←	Optimize (*1)	Same as (c)	Same as (c)
	Gas	Φ9.52	←	Optimize (*1)	Same as (c)	Same as (c)
Refrigerant charge [kg]		1.1	COP Maximum (*2)	COP Maximum (*2)	COP Maximum (*2)	COP Maximum (*2)
Capacity vs base model [%]		100	←	←	←	←
Expansion valve		As it is	Same as Base model SH	Same as Base model SH	Same as Base model SH	Same as Base model SH

※Note 1： Same as temperature-equivalent pressure drops of base model

※Note 2： Proposal under consideration

7.3.5 Application of LCCP Evaluation and Consideration

With regard to the LCCP evaluation, this chapter formulates a hypothesis for the study with a view to the influential factors and the study of regions both in Japan and abroad and describes a consideration of these.

7.3.5.1 Key Points of the Project in the LCCP Evaluation:

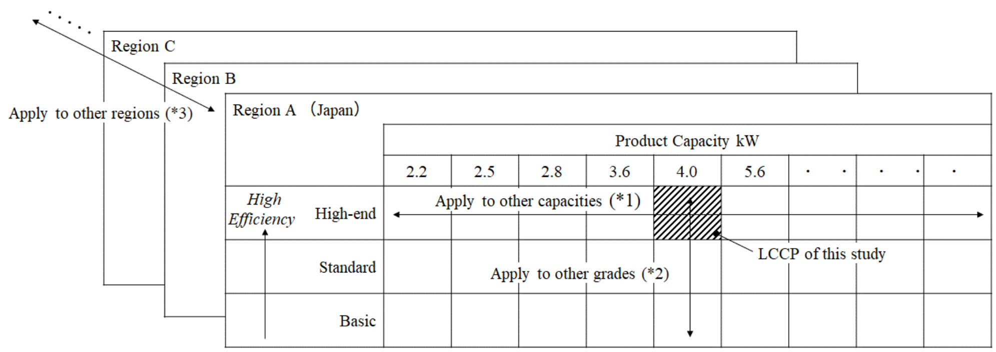
Firstly, we will explain the key points of the project in the LCCP evaluation.

The LCCP evaluation is basically examined by utilizing field data in addition to the past study by JRAIA [**2**] and the paper by UMD [**3**].

The results of the evaluation based on the actual operating conditions will be reported next time in the final report.

7.3.5.2 Application of the Project's LCCP Evaluation

The concept of the LCCP evaluation in this project is shown in Figure 7-40, and the following explains how to apply the evaluation and other matters. The final report of the project will classify and study the regional characteristics of ambient air temperatures and other influential factors in Japanese regions that affect the LCCP evaluation. Therefore, we will study the LCCP evaluation through this task, bearing in mind that other countries will be able to make broad and general speculation.



How to apply：

※Note 1, ※Note 2： Modify the simulation model (Figure 4)

※Note 3： Modify the assumption parameters (Table 6)

Figure 7-40: Outline of how to apply the LCCP of this study to various product specifications and global areas

(1) Impact of equipment specifications

As explained in 7-2-4, the LCCP values in this project are calculated for the standard model based on a high-end A.C. unit with a cooling capacity of 4kW that is commercially available in Japan.

However, there is a wide variety of A.C.s in the Japanese market, and they are even more diversified in other countries. In our view, for such diverse equipment, it is possible to calculate the annual power consumption, namely the indirect emissions in the LCCP evaluation, by modifying the specifications in the refrigeration cycle simulation shown in Figure 7-39.

(2) Influence of regional characteristics

In addition to the modification of the equipment specifications mentioned in (1), the annual power consumption, namely the indirect emissions in the LCCP evaluation, also requires modifications of the estimation parameters according to environmental characteristics, including the temperatures in the region, users' usage conditions, differences in power generation systems, and other factors.

For reference, Figure 7-41 shows a comparison of the changes in monthly average temperatures around the world in 2020. Climates vary depending on the assumed regional environment, which results in differences in the ambient air temperatures and humidity, operating hours, and required load. These differences strongly affect the annual power consumption during the use of an A.C. – the indirect emissions of LCCP. For example, in a region where ACs are required to operate throughout the year, annual power consumption is projected to increase throughout the life of the equipment. Regarding the load on the equipment, the higher the ambient air temperature during the cooling mode, the higher the condensing pressure in the refrigeration cycle, increasing the load on the compressor. The heat load entering the building from outdoors also increases, and the room temperature tends to rise; therefore, it is necessary to select an A.C. with a higher capacity.

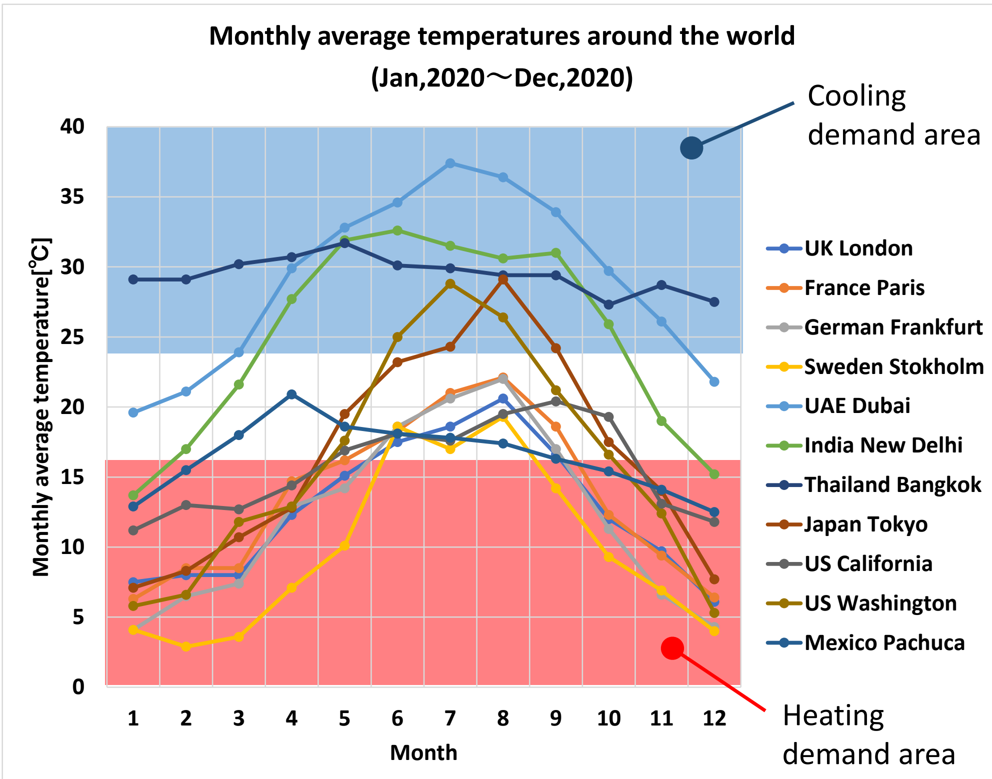


Figure 7-41: Example of monthly average temperatures around the world

Moreover, larger heat exchangers are required as the load increases, leading to the problem of an increase in the amount of refrigerant used. Therefore, it is anticipated that there will be demand for highly efficient refrigerants suitable for large capacity and other influences.

Figure 7-42 shows the composition of power generation systems in five countries in 2016. Power resources are classified into fossil fuels, such as petroleum, natural gas, and coal, and non-fossil fuels, such as hydraulic power, other renewable energies, and nuclear power, and they are compared in percentage terms. As indicated in Table 7-46, according to the resource of power generation means, LCCP is affected by E.M., which is the amount of CO_2 [$kgCO_2$] generated per unit power consumption [kWh]. The EM varies greatly depending on the major power generation systems in each country. For example, in countries where the major systems are renewable energy power generation, such as hydraulic power and nuclear power generation, the power consumed by ACs will be unlikely to lead to CO_2 emissions, and the indirect emissions will be negligible. On the other hand, in countries where power generation is mainly derived from fossil fuels such as petroleum and natural gas, CO_2 emissions from the use of A.C. become sensitive, and the indirect emissions of LCCP are strongly affected by the equipment efficiency and air-conditioning load.

Concerning the power generation systems, changes in the composition due to changes in power resource demand, shift to renewable energies and other factors may also need to be considered in future predictions.

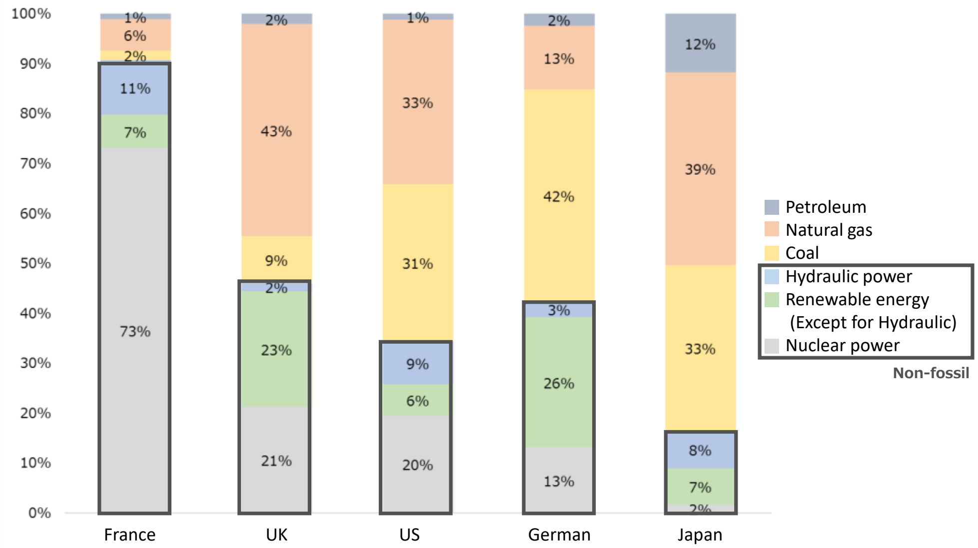


Figure 7-42: Comparison of non-fossil fuel power resource rates in 2016

In our view, by studying the basic values required for the LCCP calculation shown in Table 7-46, it is possible to apply the LCCP evaluation to the influential factors described above.

(3) Impact of the properties of various refrigerants

This section explains the concept concerning the LCCP evaluation methods for diverse candidate refrigerants.

As mentioned in Chapter 7-2-4 and this chapter, in this project, by utilizing new performance simulation with high accuracy and market data, the LCCP evaluation is expected to be closer to actual market conditions than the previous evaluation was.

The LCCP calculation for various refrigerants in this project is described in Chapter 7-2-4. The method is to examine the factors that affect the LCCP evaluation of various refrigerants through SO or by optimizing the refrigerant circuit for each refrigerant.

For example, the values for the refrigerant charge amount, C, and annual energy consumption, AEC, which are considered major influential factors, can be calculated with high levels of accuracy. In terms of the calculation conditions, it is expected that LCCP for each refrigerant can be compared by reflecting market data and regional characteristics, such as climate and refrigerant recovery rate, which vary in different countries and regions.

7.3.6 Conclusion

In Japan, LCCP evaluation is studied in a two-step process, and the concept (hypothesis) of the first step described in this report is summarized in the following bullet points:

- The concept (hypothesis) of the LCCP evaluation in this report was established by focusing on the consistency of the criteria of evaluation indicators.

- In the LCCP evaluation, a performance simulation evaluation will be carried out using JRAIA's standard tool (performance simulation program developed by Waseda University) to optimize the system in relation to candidate refrigerants.
- Performance evaluation will be carried out through a relative comparison for each refrigerant under the same capacity.
- A residential heat pump mini-split A.C. with a capacity of 4.0 kW was selected as the standard model of A.C. equipment to be examined, and calculation will be performed.
- For the standard model, mutual correction will be made between the actual equipment test data and the performance simulation data.
- The calculation conditions of LCCP were clarified so as to share the same data recognition.

In addition, in the second step, the LCCP evaluation will be studied by utilizing the market data on ACs.

Influential factors of the LCCP evaluation were clarified and parameterized so that the evaluation can be applied overseas.

Finally, the basic concept on the positioning of the LCCP evaluation in the selection of refrigerants is explained as follows.

We believe that the LCCP evaluation to be studied in Task 3 is one of the important criteria for selecting optimal refrigerants. We also feel that in order to make the evaluation more realistic, it is desirable to conduct a comprehensive evaluation from multiple perspectives, including safety, cost, sustainability, and infrastructure development, in addition to the environmental assessment through the LCCP evaluation.

7.3.7 Future plans

Regarding issues and responses to be addressed in the second step in the future, we plan to verify the concept (hypothesis) of the LCCP evaluation described in this report.

Specifically, the study will be conducted based on the results of the performance simulation to optimize ACs. In addition, the utilization of market data will also be examined.

In the second step, we plan to study the LCCP evaluation not only for Japanese regions with a temperate climate but also, by utilizing market data, for other areas in the world, such as India, where ACs are used more often.

7.3.8 Terminology

Life Cycle Climate Performance (LCCP): An index to evaluate the global warming impact of a product throughout its life, from manufacture to disposal. Based on the TEWI, the value is calculated by adding energy consumption (indirect emissions) when manufacturing the gas to be used and the leakage of the gas (direct emissions).

Global Warming Potential (GWP): Indicates the degrees of the global warming impacts of gases released in the atmosphere. On the basis of carbon dioxide (1.0), the same gas weight and same period (100 years) are assumed to allow relative comparisons of the impact of each gas. When the HFC refrigerant used for ACs is considered to have the same gas weight, its GWP is generally hundreds to thousands of times greater than that of carbon dioxide; therefore, its significant impact on global warming is regarded as a problem.

Optimization: In performance simulation, compared with the performance prediction made with conventional DI and SO, optimized performance prediction takes into account the design concept of an actual product; optimization is carried out by adjusting the component parts (piping, heat exchanger, etc.) of the refrigeration circuit so that their specifications conform to the refrigerant characteristics.

Performance simulation: A method to estimate the power consumption of the target equipment under various operating conditions using Energy Flow +M (Prof. Saito's Lab at Waseda University), which is a standard tool of JRAIA. Used to calculate annual power consumption.

Coefficient of Performance (COP): A factor used as a measure of the energy consumption efficiency of cooling equipment, etc. The value represents cooling/heating capacity per kW of power consumption.

Total Equivalent Warming Impact (TEWI): A method to evaluate global warming impacts in comprehensive consideration of refrigerant leakage during equipment use, emissions into the atmosphere at the time of disposal, and the amount of carbon dioxide generated from fossil fuel usage due to operating power consumption. TEWI is expressed by the following equation.

TEWI = Direct CO_2 emission equivalent + Indirect CO_2 emission equivalent

Direct CO_2 emission equivalent = $\mathrm{GWP} \times L \times N + \mathrm{GWP} \times M \times (1\text{-}\alpha)$
Indirect CO_2 emission equivalent = $N \times E \times \beta$

GWP: Global warming potential per kg on the basis of CO_2, 100-year integration period (kg-CO_2e/kg)
L: Annual amount of leakage from equipment (kg/year)
N: Service life of equipment (years)
M: Amount of charge to equipment (kg)
α: Recovery rate at equipment disposal
E: Annual energy consumption of equipment (kWh/year)

β: CO_2 emissions required for 1 kWh of power generation (kg-CO_2e/kWh)

CO_2 emissions: Total of the amount of carbon dioxide generated from fossil fuel usage due to power consumption and the equivalent amount of carbon dioxide using GWP to the degree of the global warming impact of the gas released into the atmosphere.

7.3.9 References

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