



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

Volume 4

Group for Safety Evaluation

Safety and Performance Evaluation of Low-GWP Refrigerant Mixtures

FY2023-2025 Progress Report

September 2026

New Energy and Industrial Technology Development Organization (NEDO)

Contents

1. Overview of Research and Development and Outcomes.....	1
2. Study on the Safety of Self-Decomposition Reactions of HFO Refrigerants (Central Research Institute of Electric Power Industry).....	5
2.1 Introduction.....	5
2.2 International standards for refrigerant stability and trends in the addition of stability classification	5
2.2.1 Safety classification of refrigerants under ISO 817	5
2.2.2 Trends in the addition of stability classification	7
2.3 Comparison of self-decomposition reaction evaluation methods and screening for international standardization...	7
2.3.1 Comparison of various evaluation methods	7
2.3.2 Proposed method: Fusing wire and discharge method	9
2.4 Investigation of the input energy using the fusing wire and discharge method	11
2.4.1 Discharge behavior in the fusing wire and discharge test	11
2.4.2 Evaluation up to fusing	12
2.4.3 Evaluation of arc discharge	14
2.4.4 Discussion on the instability of arc discharge.....	17
2.5 Interlaboratory comparison test	18
2.5.1 Test apparatus.....	18
2.5.2 Test conditions	19
2.5.3 Test procedure.....	19
2.5.4 Test results	20
2.6 Summary.....	21
3. Development of Self-Decomposition Reaction Evaluation Methods and Study of HFO-1123 Refrigerant Mixtures (AGC).....	23
3.1 Background and objectives of research and development	23
3.1.1 Social demand for international standardization of self-decomposition reaction evaluation methods	23
3.1.2 Importance of developing ignition methods for international standardization.....	24
3.2 Issues with existing ignition methods and consideration of improvements	25
3.3 Evaluation of the effects of various parameters on the discharge behavior of the fusing wire and discharge method	28
3.3.1 Effects of the electrode gap, metal species, and wire diameter of the metal fine wire.....	29
3.3.2 Effects of the discharge atmosphere (gas species and pressure)	32
3.4 Validation of the fusing wire and discharge method	33
3.4.1 Interlaboratory comparison test for confirmation of consistency	33
3.4.2 Comparative evaluation with different ignition methods	34
3.4.3 Effect of test temperature on the propagation boundary conditions of self-decomposition reactions.....	36
3.5 Development of HFO-1123 refrigerant mixtures.....	37
3.6 Summary.....	38
4. Development of Self-Decomposition Reaction Evaluation Methods and Safety Verification of Refrigerant Mixtures Containing R1132(E) (Daikin Industries)	39

4.1 Development of self-decomposition reaction evaluation methods	39
4.1.1 Overview of the evaluation apparatus.....	39
4.1.2 Parameters affecting discharge behavior.....	40
4.1.3 Evaluation conditions for self-decomposition reactions	43
4.1.4 ILC test	43
4.1.5 Evaluation of vessel dependence	44
4.2 Clarification of the boundaries of the self-decomposition reactions of R1132(E)/R1234yf refrigerant mixtures under various conditions	44
4.2.1 Boundaries of the self-decomposition reactions in R1132(E)/R1234yf refrigerant mixtures	44
4.2.2 Comparison with the dielectric breakdown method.....	45
4.3 Elucidation of the mechanism of self-decomposition reactions.....	46
4.4 Issues and responses regarding the practical implementation of safety measures for the dissemination of next-generation low-GWP refrigerants	47
4.4.1 Examination of a mechanism to prevent equipment patents held by multiple companies from becoming obstacles to the adoption of next-generation low-GWP refrigerants	47
4.4.2 Examination of a mechanism to prevent the inability to utilize next-generation low-GWP refrigerants owing to a lack of know-how	48
4.4.3 Examination of a mechanism for effective public promotion	48
5. Identification of Factors Inducing Self-Decomposition Reactions in Compressors and Development of an Energy Evaluation Method (Suwa University of Science)	50
5.1 Introduction.....	50
5.2 Research methodology.....	51
5.2.1 Short-circuit experimental apparatus and method.....	51
5.2.2 Numerical simulation method.....	53
5.3 Results and discussion	53
5.3.1 Experimental results of phase-to-phase short circuits in the inverter compressor (single-phase 200 V unit)	53
5.3.2 Experimental results of phase-to-phase short circuits in the inverter compressor (single-phase 100 V unit)	57
5.3.3 Experimental results of phase-to-phase short circuits in the constant-speed compressor	58
5.3.4 Numerical simulation results for phase-to-phase short circuits in the inverter compressor	60
5.4 Summary and future work	62
APPENDIX: Safety Evaluation in Actual Use of Refrigerants With the Potential for Self-Decomposition Reactions (The Japan Refrigeration and Air Conditioning Industry Association).....	64
A.1 Self-decomposition reactions.....	64
A.1.1 Self-decomposition reaction limit	65
A.1.2 Concept of the conditions for the occurrence of self-decomposition reactions in actual equipment	65
A.2 Framework for self-decomposition reaction risk assessment.....	66
A.2.1 Risk assessment item 1 (basic form).....	66
A.2.2 Risk assessment item 2 (related to the self-decomposition reaction limit line; examination for identifying the usable range)	66
A.3 Self-decomposition reaction scenarios and examination of reachable conditions	67

A.4 Estimation of the maximum input energy	68
A.4.1 Measurement of the discharge energy in an inverter for RAC	68
A.4.2 Setting the maximum input energy for inverters	69
A.5 Estimation of the maximum R1132(E) composition ratio	69
A.5.1 Concept of a simplified estimation of composition change	70
A.5.2 Simplified calculation method for the maximum R1132(E) composition ratio	70
A.6 Estimation of the self-decomposition reaction limit line and the R1132(E) limit composition ratio	71
A.6.1 Trend of the self-decomposition reaction limit line with respect to the R1132(E) composition ratio	72
A.6.2 Trend of Reachable Scenario Conditions	72
A.6.3 Setting the R1132(E) Limit Composition Ratio	72
A.7 FTA for Hazardous Scenarios	74
A.7.1 Results of the Reachable Condition Verification Test for Scenario No. 9	74
A.7.2 FTA for Scenario No. 9	75
A.8 Equipment Specifications Currently Considered Capable of Avoiding Self-Decomposition Reactions	76
A.8.1 Calculation of the Proportion of Accumulated Refrigerant	76
A.8.2 Judgment of Whether Self-Decomposition Reactions Are Avoidable	77
A.9 Summary and future activities	78

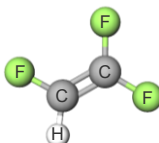
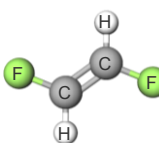
1. Overview of Research and Development and Outcomes

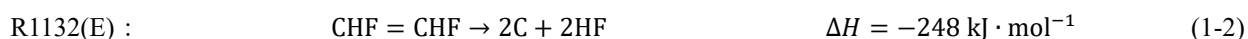
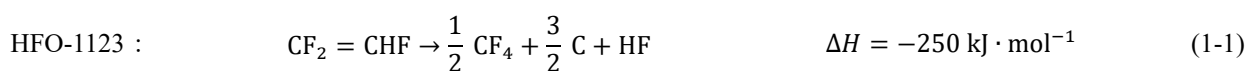
Hydrofluorocarbons (HFCs), which were developed as substitutes for specified chlorofluorocarbons from the standpoint of ozone-layer protection, have a high global warming potential (GWP) and are designated as gases subject to emission reduction under the Kyoto Protocol and the Paris Agreement. Furthermore, under the Kigali Amendment to the Montreal Protocol adopted in 2016, developed countries, including Japan, are required to reduce HFC production and consumption by 85% by 2036 relative to the 2011–2013 average. Because this target is unlikely to be achieved with the continued use of existing refrigerants, the early development of low-GWP refrigerants, together with refrigeration and air conditioning equipment using such refrigerants, is indispensable. Among refrigeration and air conditioning equipment, residential and commercial air conditioners and small commercial refrigeration equipment still rely on HFC refrigerants, despite accounting for large in-use refrigerant stocks and representing major sources of atmospheric leakage. In particular, for residential air conditioners and similar equipment for which substitute refrigerants have yet to be determined, it is essential to accelerate the development and dissemination of next-generation low-GWP refrigerants and associated equipment by establishing equipment design guidelines as core technologies, based on an integrated approach spanning refrigerant screening, equipment development, and performance evaluation.

Hydrofluoroolefin (HFO)-based refrigerants have attracted attention as next-generation refrigerants for achieving a lower GWP. These substances contain carbon–carbon double bonds in their molecular structures and are generally characterized by extremely low GWP and relatively low flammability. Among the next-generation HFO refrigerants for air conditioning and refrigeration applications, HFO-1123 ($\text{CF}_2=\text{CHF}$) and R1132(E) ($\text{CHF}=\text{CHF}$) have attracted particular attention. Because their thermophysical properties are close to those of R32 (CH_2F_2), which is currently a widely used refrigerant, they are considered promising candidates for residential and commercial air conditioning, electric vehicle air conditioning, and refrigeration applications (In this chapter, HFO-1123, R1132(E), and mixtures containing these substances are collectively referred to as next-generation low-GWP refrigerants). Concurrently, these next-generation low-GWP refrigerants have been reported to be susceptible to the self-decomposition reactions described subsequently; therefore, they require safety evaluations beyond conventional refrigerant safety indicators such as flammability and toxicity.

A self-decomposition reaction is a chemical reaction in which two or more of the same type of molecules react with each other under externally supplied energy and decompose into two or more different products. The aforementioned next-generation low-GWP refrigerants are known to be capable of undergoing self-decomposition reactions. The chemical reaction equations are shown in Equations (1-1) and (1-2). These reactions generate hydrogen fluoride and carbon (soot). In the case of these refrigerants, the reactions are also exothermic.

Table 0-1 HFO-1123 and R1132(E)

HFO-1123	R1132(E)
$\text{CF}_2=\text{CHF}$	$\text{CHF}=\text{CHF}$
GWP < 1	GWP < 1
	



In self-decomposition reactions of next-generation low-GWP refrigerants, the following three factors are generally identified as contributing factors:

- Pressure and temperature: reactions are more likely to propagate under high-pressure and high-temperature conditions.
- Refrigerant composition: reactions are more likely to propagate when the composition of HFO-1123 or R1132(E) is high.
- Input energy: external energy input is required to initiate the reaction. The greater the energy input, the more readily the reaction propagates.

Figure 1.1-1 shows a schematic of the three factors described above (Figure 1.1-1(a)) and another showing the reaction propagation boundaries (Figure 1.1-1(b)–(d)). In Figure 1.1-1(b), the region above the reaction propagation boundary indicated by the red line (the high-pressure/high-temperature region) represents conditions under which the self-decomposition reaction propagates, whereas the region below it indicates conditions under which it does not propagate. This reaction propagation boundary varies depending on the conditions. Figure 1.1-1(c) illustrates the effect of refrigerant composition, showing that the reaction propagation boundary shifts upward when the composition of HFO-1123 or R1132(E) is lower; that is, reaction propagation becomes less likely. In addition, Figure 1.1-1(d) shows the effect of input energy magnitude, indicating that the reaction propagation boundary shifts downward as the input energy increases; that is, reaction propagation becomes more likely.

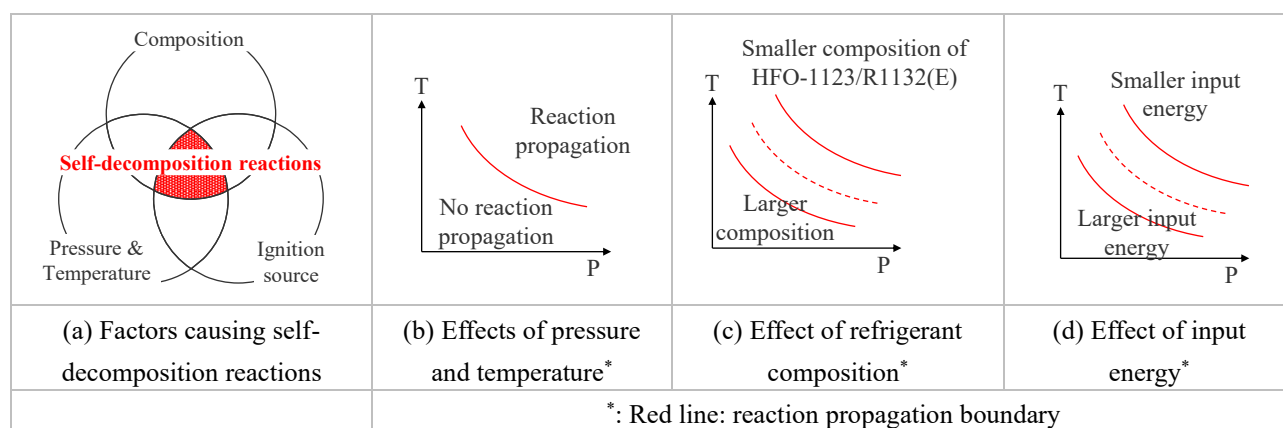


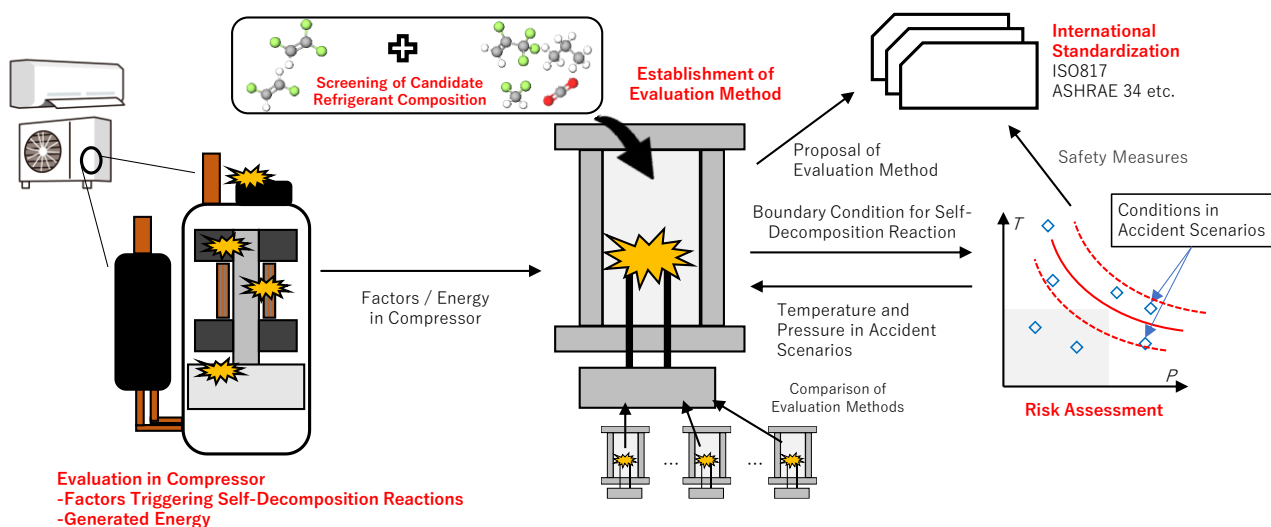
Figure 0-1 Factors causing self-decomposition reactions

The occurrence of self-decomposition reactions is considered unlikely when refrigerant leaks from the refrigeration cycle and reaches atmospheric pressure because it requires high-pressure and high-temperature conditions. However, unlike combustion, self-decomposition does not require oxygen, and a new safety risk has been identified in that the reaction may occur within the refrigeration cycle. Refrigeration cycles comprise various components, among which the compressor is considered to present the highest accident risk involving self-decomposition reactions. Compressors incorporate motors and compression mechanisms, and in relatively small compressors for applications such as residential air conditioners, where next-generation low-GWP refrigerants are expected to be used, the motor coils are cooled via direct contact with the refrigerant. For example, if abnormal operation leads to high pressure and high temperature inside

the system and the electrical insulation disintegrates, resulting in discharge, a self-decomposition reaction may occur within the compressor. As noted above, the self-decomposition reactions of HFO-1123 and R1132(E) are exothermic; therefore, the reaction results in increases in pressure and temperature and, in the worst case, may lead to compressor rupture.

Against this background, the Group for Safety Evaluation (Safety Gr.; comprising the Central Research Institute of Electric Power Industry (CRIEPI), Suwa University of Science, AGC, and Daikin Industries) is conducting safety and performance evaluations of next-generation low-GWP refrigerants. Figure 1.1-2 presents a schematic overview of the research and development items undertaken by Safety Gr. The principal activities are as follows:

- Identifying the factors inducing self-decomposition reactions and developing an energy evaluation method: This involves evaluating the energy sources generated within compressors and their energy levels, which are considered to pose the highest risk as factors inducing self-decomposition reactions.
- Developing self-decomposition reaction evaluation methods: The existing and proposed methods for assessing the self-decomposition reactions in next-generation refrigerants are compared, and an evaluation method is developed with future standardization considerations.
- Narrowing down refrigerant compositions: This involves narrowing down refrigerant compositions, considering safety, environmental performance, and performance from the perspective of self-decomposition reactivity.
- Risk assessment: The safety risks related to self-decomposition reactions during actual use are evaluated based on accident scenarios with real equipment and under reachable temperature and pressure conditions.
- International standardization: This involves incorporating additional revisions concerning safety related to self-decomposition reactions into international standards for refrigerant safety classification and safety/environmental requirements.



- Figure 0-2 Overview of the research and development items undertaken by the Group for Safety Evaluation

Among the research and development items described above, risk assessment is conducted in collaboration with the Japan Refrigeration and Air Conditioning Industry Association (JRAIA; indicated as JRAIA in the figure) via a self-decomposition reaction study group. Figure 1.1-3 shows the organizational structure of the self-decomposition reaction study group (indicated in the figure as the “Self-Decomposition Reaction Study Group”). From the NEDO project participants, the four Safety Gr. organizations—CRIEPI, Suwa University of Science (SUS in the figure), AGC, and Daikin Industries (DAIKIN in the figure)—together with the National Institute of Advanced Industrial Science and Technology (AIST in the figure), NEDO, and PL, participate; from JRAIA, the Self-Decomposition Reaction Risk Study Working Group and the secretariat also participate. As shown in this figure, the practical implementation of these

refrigerants is being promoted through collaborations across industry, government, and academia. The activities of the JRAIA Self-decomposition Reaction Risk Study Working Group are described in the appendix to this chapter.

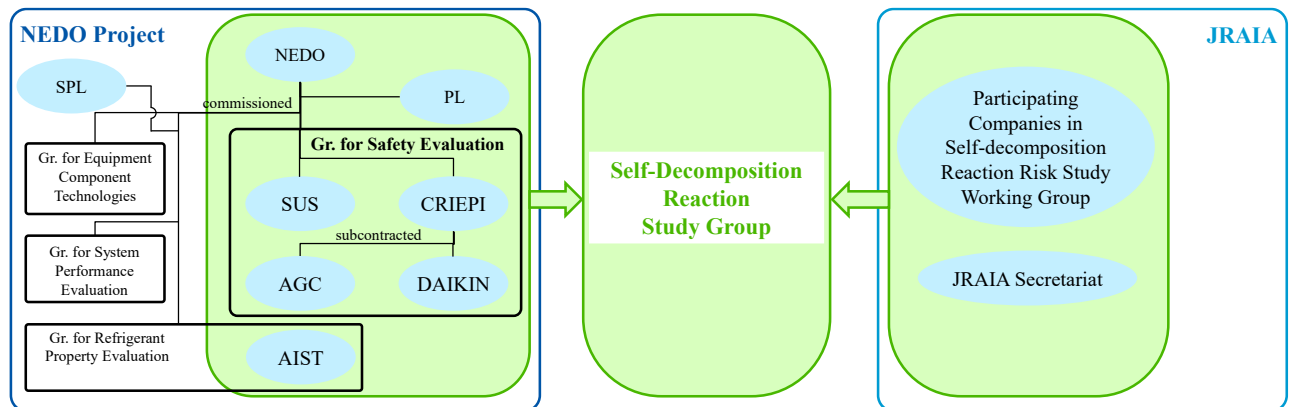


Figure 0-3 Self-Decomposition Reaction Risk Study Working Group

These research and development efforts make it possible to clearly assess the risk of self-decomposition reactions by comparing the discharge energy corresponding to various short-circuit modes in actual residential air conditioning equipment with data on the occurrence limits of self-decomposition reactions. This will contribute to ensuring the safe implementation and international standardization of low-GWP refrigerants and support revisions to international standards that define refrigerant stability classifications. In addition, refrigerant compositions judged to be safe from the standpoint of self-decomposition reactions will be identified, and verifying the risks during actual use will clarify the requirements for refrigerants and equipment and their safety levels. Furthermore, by coordinating with other groups participating in the NEDO project, refrigerant compositions with superior safety, environmental performance, and cycle performance will be refined to a core set, and equipment design guidelines for maintaining and improving performance will be presented. These outcomes are expected to facilitate the achievement of the Paris Agreement and Kigali Amendment targets, as well as the practical implementation of next-generation HFO refrigerants by refrigerant and equipment manufacturers.

2. Study on the Safety of Self-Decomposition Reactions of HFO Refrigerants

(Central Research Institute of Electric Power Industry)

2.1 Introduction

As described in the preceding section, next-generation low-GWP refrigerants such as HFO-1123 and R1132(E) have excellent low-GWP characteristics; however, they also raise safety concerns related to self-decomposition reactions. If this reaction occurs inside a compressor, the pressure may rise rapidly and cause serious accidents such as compressor rupture, which has become an obstacle to practical implementation and widespread adoption. In addition to excellent environmental performance (low GWP) and safety (low self-decomposition reactivity and flammability), excellent cycle performance when used as a refrigerant (high refrigerant performance) is also required.

In the preceding NEDO project conducted in fiscal years 2018–2022, “Development of Next-Generation Refrigerants, Refrigeration and Air-Conditioning Technologies, and Evaluation Methods to Achieve Energy Conservation and Low Greenhouse Gas Emissions” (hereinafter referred to as the preceding project), the conditions under which self-decomposition reactions occur in HFO refrigerants and their refrigerant mixtures containing them were investigated. However, the test methods were not unified, and it has been pointed out that the boundary conditions for the occurrence of self-decomposition reactions differ depending on the evaluation method (NEDO, 2023). International standardization of safety related to self-decomposition reactions is crucial for the practical implementation and widespread adoption of next-generation low-GWP refrigerants; to this end, the standardization of evaluation methods, including test methods and judgment criteria, is essential.

This section outlines the efforts toward revising refrigerant stability classifications. The trends in revising the international standards are introduced, and the development of evaluation methods for adding stability classifications related to self-decomposition reactions, as well as interlaboratory comparison tests conducted to verify their validity, is described.

2.2 International standards for refrigerant stability and trends in the addition of stability classification

2.2.1 Safety classification of refrigerants under ISO 817

In the current standards, the safety classification of refrigerants is specified in ISO 817:2024 (Refrigerants — Designation and Safety Classification) of the ISO standards (ISO, 2024a). This standard defines refrigerant safety classifications from two perspectives: flammability and toxicity.

In terms of flammability, as shown in Table 2.2-1, refrigerants are classified into four categories: 1, 2L, 2, and 3. If flame propagation does not occur at 60 °C and 101.3 kPa, the refrigerant is classified as Class 1. Conversely, if flame propagation is observed, the refrigerant is classified based on the lower flammability limit (LFL), heat of combustion (HOC), and maximum burning velocity (BV_{max}). The test method for determining the LFL is specified in ASTM E681 (Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)), in which an electric discharge is applied to the refrigerant in a glass flask (ASTM International, 2015). The burning velocity is determined in accordance with ISO/PAS 24499 (Method of test for burning velocity measurement of A2L flammable gases) or another reliable method. ISO/PAS 24499 specifies the vertical glass tube method as the method for measuring the burning velocity (ISO, 2024b).

Table 0-1 Flammability classification

Class		Flame propagation*	LFL**	HOC***	BV _{max} ****
Class 1	No Flame Propagation	No			
Class 2L	Lower flammability	Yes	> 3.5 vol%	and < 19000 kJ•kg ⁻¹	and ≤ 10 cm•s ⁻¹
Class 2	Flammable	Yes	> 3.5 vol%	and < 19000 kJ•kg ⁻¹	
Class 3	Higher flammability	Yes	≤ 3.5 vol%	or ≥ 19000 kJ•kg ⁻¹	

*: tested in air at 60 °C and 101.3 kPa; **LFL: lower flammability limit;

HOC: heat of combustion; *BV_{max}: maximum burning velocity.

In terms of toxicity, refrigerants are classified into categories A and B, as outlined in Table 2.2-2, where Class A indicates lower toxicity, and Class B indicates higher toxicity.

Table 0-2 Toxicity classification

Class	Mortality TCF*	TCF* of cardiac sensitization, anaesthetic or central nervous system, and other escape impairing and permanent injury.	OEL**
Class A	≥ 2500 ppm	and ≥ 10000 ppm	and ≥ 150 ppm
Class B	< 2500 ppm	or < 10000 ppm	or < 150 ppm

*TCF: toxic concentration factor; **OEL: occupational exposure limit.

In the previous edition revised in 2014, the toxicity classification was based only on chronic toxicity according to the occupational exposure limit (OEL). Refrigerants with an OEL of 400 ppm or higher were classified as Class A, and those with an OEL below 400 ppm were classified as Class B (ISO, 2014). In the 2024 edition, the following revisions were made:

- The classification criteria based on OEL were relaxed.
- Acute toxicity was introduced as an additional criterion.

Consequently, the toxicity classifications of some refrigerants were reviewed.

As another international standard for refrigerant safety, ASHRAE Standard 34—Designation and Safety Classification of Refrigerants, issued by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), also exists and classifies refrigerants using the same four flammability classes and two toxicity classes (ASHRAE, 2024). For flammability, largely similar test methods are adopted, although the classification boundaries are slightly different, and discussions regarding their harmonization are ongoing. For toxicity, ASHRAE still uses an OEL-only-based classification; however, discussions are ongoing to revise the standard to incorporate classification based on acute toxicity, as in the ISO.

As described above, refrigerant safety classifications are defined according to flammability and toxicity, and classifications such as A1 and B2 are assigned according to combinations of these two criteria. For example, R744 (carbon dioxide) is classified as A1, R32 as A2L, R290 (propane) as A3, and R717 (ammonia) as B2L.

2.2.2 Trends in the addition of stability classification

As noted above, refrigerant safety classifications are based on flammability and toxicity; however, the current classification system does not address issues related to stability, such as self-decomposition reactions. In response to the emergence of next-generation low-GWP refrigerants that may undergo self-decomposition reactions, TF3 (Refrigerant stability classification) was established under Japanese leadership in June 2024 within ISO/TC86/SC8 (Refrigerants and refrigeration lubricants). This initiated a commitment to revise ISO 817 to incorporate refrigerant stability classifications.

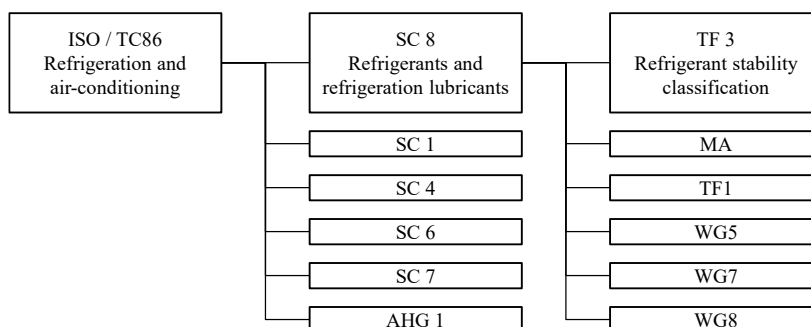


Figure 0-1 ISO/TC86 and TF3 (ISO/TC86 Website, 2026)

As of March 2026, TF3 mainly discussed the following key items toward establishing refrigerant stability classifications:

- Definition of refrigerant stability classes: The following three categories are currently under consideration:
 - Class α : Sufficient stability for general use.
 - Class β : Sufficient stability under controlled conditions.
 - Class γ : Unstable and shall not be used.
- Test apparatus.
- Test conditions.

If this revision of the standard is adopted, refrigerant safety classifications will be expressed in forms such as A1 α and A2L β .

For this revision of the standard, both the test apparatus and evaluation method must be developed and specified. The following section describes the efforts toward developing the evaluation method.

2.3 Comparison of self-decomposition reaction evaluation methods and screening for international standardization

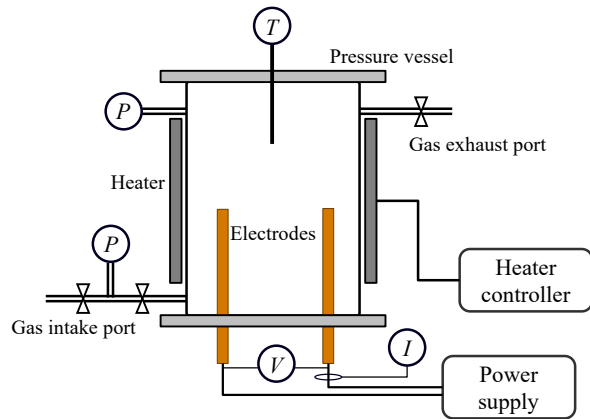
2.3.1 Comparison of various evaluation methods

As described above, because self-decomposition reactions occur under high-temperature and high-pressure conditions, their evaluation is also conducted under similar conditions. Figure 2.3-1 shows an image and a schematic diagram of the fabricated self-decomposition reaction evaluation apparatus. Electrode rods are inserted into a cylindrical reaction vessel capable of withstanding pressures up to 50 MPa, with an internal volume of 314 cm³. Electrodes can be attached to the tips of these electrode rods, and the structure enables energy supply to the refrigerant by feeding current from an external source. In addition, heaters are installed around the reaction vessel, enabling a temperature increase to 150 °C. The occurrence or absence of propagation of a self-decomposition reaction is evaluated based on the refrigerant pressure and temperature after ignition. A stabilized power supply (NF Corporation, DP090S) was used to apply voltage to the electrodes. The current limit, applied voltage, and application time can be set on the power supply side. The pressure and temperature of the refrigerant inside the reaction vessel were measured using a pressure gauge (Nagano Keiki, KJ16,

accuracy $\pm 0.5\%$ F.S.) and a thermometer (K-type thermocouple, accuracy $\pm 1.35\text{ }^{\circ}\text{C}$), respectively. Current and voltage were measured using an ammeter (Hioki, CT6876, accuracy $\pm 0.04\%$ F.S.) and a voltmeter (Keyence, NR-HV04, accuracy $\pm 0.4\text{ V}$), respectively.



(a) Image



(b) Schematic diagram

Figure 0-1 Self-decomposition reaction evaluation apparatus

For the standardization of the self-decomposition reaction evaluation, it is necessary to specify the configuration of the test apparatus and the test method, including the temperature, pressure, and ignition method; that is, the method for supplying energy to the refrigerant. Among these, the ignition method, by which the energy required to initiate the reaction is supplied, is particularly important.

Several methods such as those listed below have been devised to date, and next-generation low-GWP refrigerants have been evaluated using these methods (Higashi *et al.*, 2026).

- **Fusing wire method:**
A thin metal wire with a diameter of less than 1 mm is placed between the electrodes. When current is applied, the thin metal wire is heated and eventually reaches its melting point and fuses. Through this process, energy is supplied to the refrigerant (Otsuka *et al.*, 2018a). The amount of input energy depends on the volume of the metal wire. However, because most of the input power is consumed when heating and melting the metal, identifying the actual amount of heat transferred to the refrigerant is challenging.
- **Discharge method (movable electrodes):**
This method uses electrodes comprising two opposing bolts suspended by a metal plate. When current is applied while the bolt tips are in contact with each other, the bolts move owing to an electrical repulsive force, and arc discharge occurs in the resulting small gap. The amount of input energy is controlled by the current value and energization time. This method enables arc discharge to be generated easily. However, because the amount of input energy also depends on bolt movement, it may be affected by factors such as the force with which the metal plate presses the bolts together, and accurate energy control has been reported to be difficult (Otsuka *et al.*, 2018b).
- **Discharge method (spiral electrodes):**
An electrode structure is formed by partially overlapping two copper helical electrodes; that is, spiral electrodes. When current is applied, the electrodes electrically repel each other, producing a small gap where an arc voltage is generated. The amount of input energy is controlled by the current value and energization time (Zhang *et al.*, 2023). This method also enables arc discharge to be generated easily; however, delicate adjustment of the electrodes is necessary to accurately regulate the input energy.
- **Discharge method (dielectric breakdown):**
Needle electrodes are arranged to face each other. A high voltage of 40 kV is applied instantaneously to induce

dielectric breakdown, and the energy stored in a capacitor is released as arc discharge. The amount of input energy is controlled by the charge stored in the capacitor. This method enables the input energy to be controlled easily. However, a high-voltage booster circuit is required, and conducting tests in a refrigerant atmosphere at pressures exceeding 3 MPa is challenging (Goto *et al.*, 2023).

- Hot-spot method:

In this method, current is applied to a metal wire for a specified period, thereby forming a localized heat source via Joule heating (Goto *et al.*, 2023). The amount of input energy must be estimated separately.

As described above, self-decomposition reactivity tests of next-generation low-GWP refrigerants have been conducted using multiple ignition methods; however, it has become clear that the results differ by method. Evaluation results for self-decomposition reactions obtained in the preceding project by different operators and ignition methods (NEDO, 2023) were organized to facilitate a comparison of the amount of input energy and the ignition methods. Figure 2.3-2 shows an example of the comparison results. Even when tests are performed using the same refrigerant under the same conditions, the boundary conditions for self-decomposition reactions differ significantly depending on the ignition method. Therefore, developing and establishing an ignition method suitable for international standardization is considered crucial.

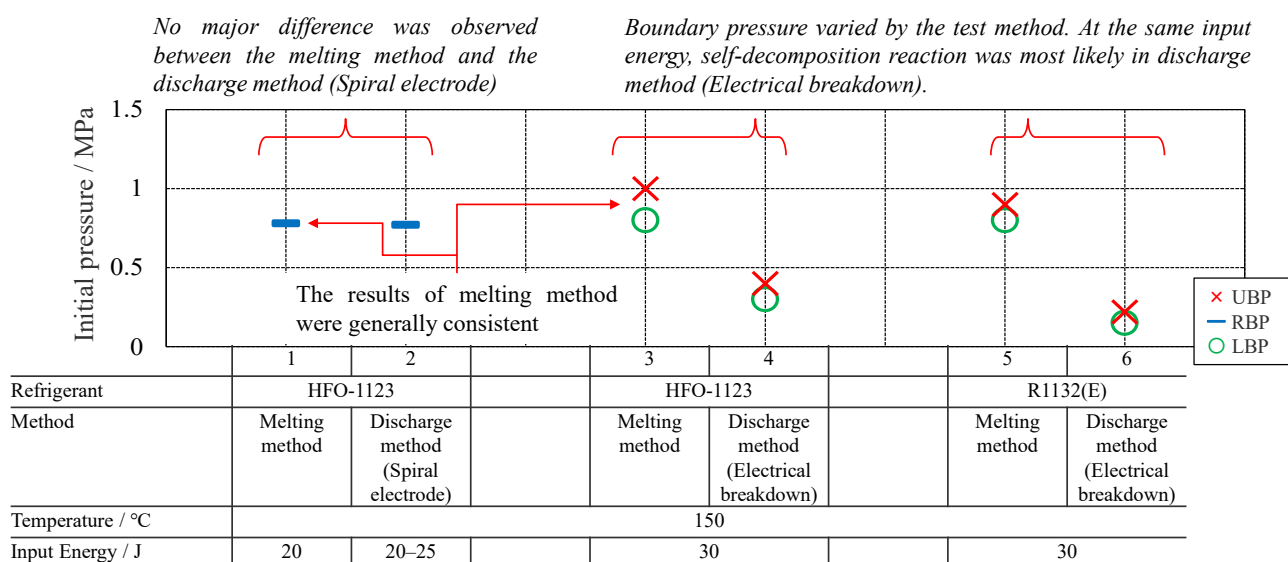


Figure 0-2 Comparison of different methods for self-decomposition reaction evaluation

*: UBP: Upper bound pressure; RBP: Reaction boundary pressure; LBP: Lower bound pressure.

2.3.2 Proposed method: Fusing wire and discharge method

As described above, various evaluation methods have been used to date. In the international standardization of an evaluation method, the following requirements are considered important:

- Reproducibility: Consistent results can be obtained when tests are repeated or when tests are performed by different operators.
- Simplicity: The test method is simple and easy to perform.
- Controllability of the input energy: The amount of energy supplied to the refrigerant can be quantified and adjusted.

Focusing on the third requirement, using arc discharge to supply energy to the refrigerant is desirable because the amount of energy can be calculated directly from the measured current and voltage values. However, fluorocarbon refrigerants have high insulating properties, and forming arc discharge is relatively difficult, particularly under high-

pressure conditions. If the arc discharge becomes unstable, the amount of supplied energy also fluctuates. Therefore, the following additional requirement is necessary for international standardization.

- Stable discharge can be achieved even in a high-pressure refrigerant atmosphere.

Based on these requirements, the fusing wire and discharge method was selected as a promising test method for international standardization. Figure 2.3-3 shows a schematic diagram of this method. The test procedure outline is as follows:

- A thin metal wire, namely a fusing wire, is installed between electrodes placed several millimeters apart.
- When current is applied to the fusing wire, its temperature rises owing to Joule heating, and it eventually reaches its melting point and fuses. The metal vapor generated from the fusing wire promotes the formation of arc discharge.
- Arc discharge occurs between the electrodes. This supplies the refrigerant with the energy required to initiate a self-decomposition reaction.

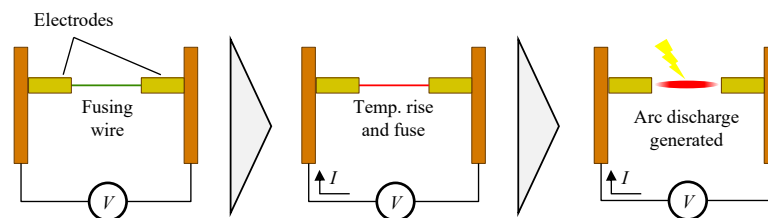


Figure 0-3 Fusing wire and discharge method

Figure 2.3-4 shows the electrodes installed in the test apparatus (Figure 2.3-1). Two copper electrodes with a diameter of 3 mm were arranged horizontally to face each other with an interelectrode gap of 1 mm, and a fusing wire, specifically a nickel wire with a diameter of 0.1 mm, was soldered between them. This method, in which a thin metal wire is installed between electrodes to generate discharge, has been standardized in international standards such as EN 1839 (Determination of the explosion limits and the limiting oxygen concentration of flammable gases and vapors) and TDG (the United Nations' Recommendations on the Transport of Dangerous Goods). However, because the evaluation target is a high-pressure fluorocarbon refrigerant, for which discharge is considered difficult, and because the required energy level differs, it is necessary to specify various requirements and evaluate their validity specifically for evaluating refrigerant self-decomposition reactions.

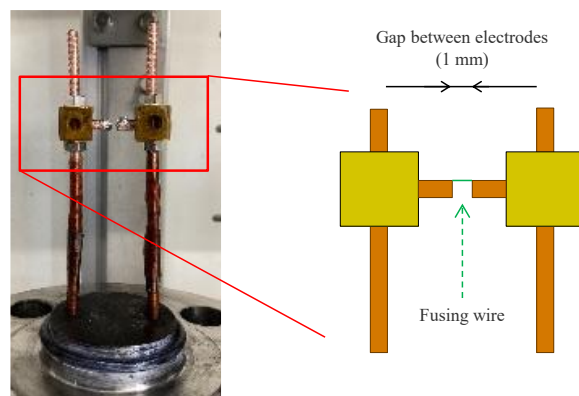


Figure 0-4 Electrodes used in the fusing wire and discharge method

2.4 Investigation of the input energy using the fusing wire and discharge method

This section examines the evaluation and prediction of the input energy supplied to the refrigerant using the fusing wire and discharge method described above (Higashi *et al.*, 2025a).

2.4.1 Discharge behavior in the fusing wire and discharge test

Figure 2.4-1 shows images of the discharge behavior in the fusing wire and discharge test. After the start of energization, the fusing wire temperature increased, and arc discharge occurred after the wire fused. From 2.5 to 10.0 ms, intense light emission was observed between and above the electrodes. At 12.5 ms, the current was interrupted by the power supply, and the arc was extinguished.

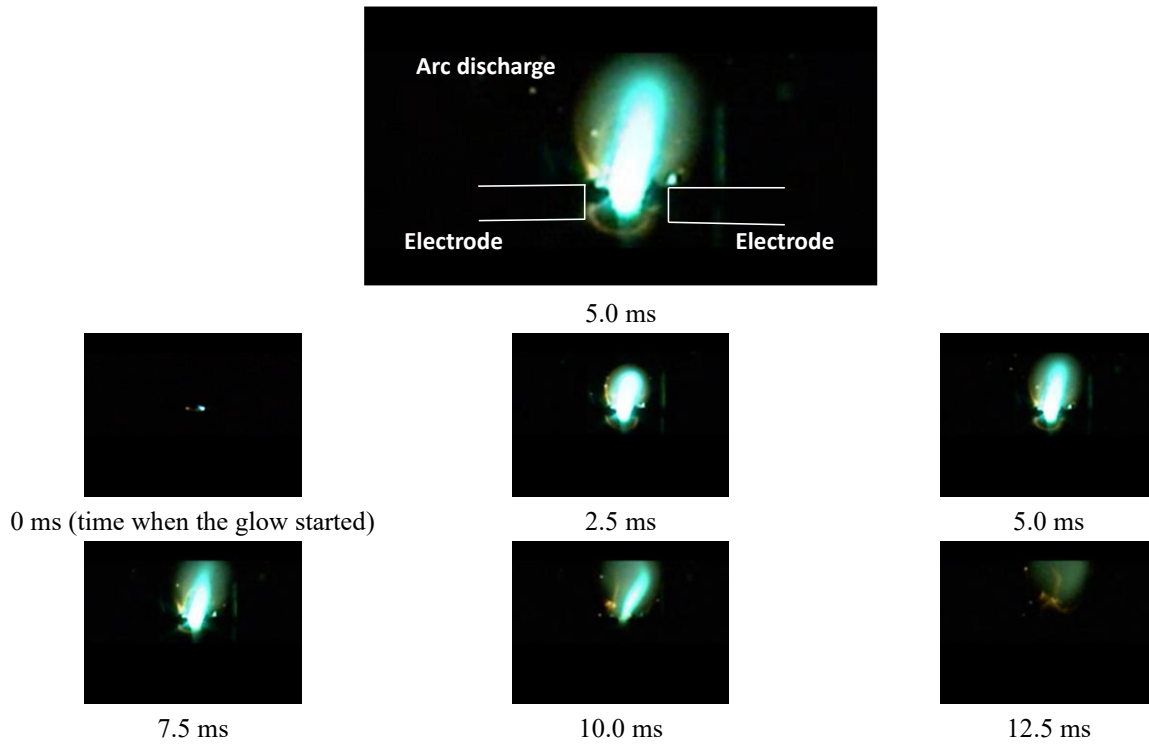


Figure 0-1 Images of the fusing wire and discharge test
(N₂, ambient temperature, 0.1 MPa, electrode distance: 2.5 mm)

Figure 2.4-2 shows an example of the changes in current and voltage during fusing in the fusing wire and arc discharge method. The experimental conditions were the same as those in Figure 2.4-1. The voltage gradually increased as the fusing wire melted and reached its maximum at the time of fusion. Thereafter, the voltage during arc discharge was maintained almost constant. Figure 2.4-3 shows a schematic diagram of the changes in current and voltage. These changes consist broadly of (i) the process until the wire fuses (up to t_{fus}) and (ii) the arc discharge process (up to t_{arc}), as expressed in Equation (2.4-1). The phenomena and amount of input energy in each process are evaluated below to predict and control the amount of energy supplied to the refrigerant under evaluation.

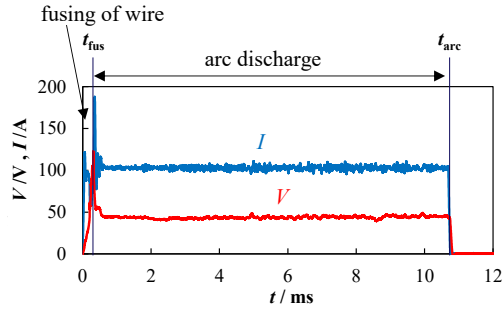


Figure 0-2 Change in voltage and current

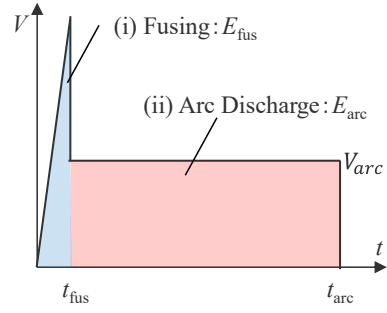


Figure 0-3 Schematic diagram of the change in voltage during the fusing wire and discharge method

$$E_{\text{total}} = E_{\text{fus}} + E_{\text{arc}} \quad (2.4-1)$$

2.4.2 Evaluation up to fusing

Simulations based on the physical properties of the fusing wire material were performed to predict the changes in current, voltage, and temperature during the fusing process. The melting point, electrical resistivity, enthalpy, and other physical properties of metals were obtained from the Thermophysical Property Database of the National Institute of Advanced Industrial Science and Technology (AIST) (AIST, 2018) and from previous studies (Ikeda, 1988). Figure 2.4-4 shows an example of the physical properties of nickel. The horizontal axis represents temperature, and the vertical axis represents electrical resistivity and specific heat, both of which are expressed as functions of temperature. Nickel loses its ferromagnetic properties at the Curie temperature ($T_C = 358 \text{ }^\circ\text{C}$), and its physical properties change substantially, as shown in the figure.

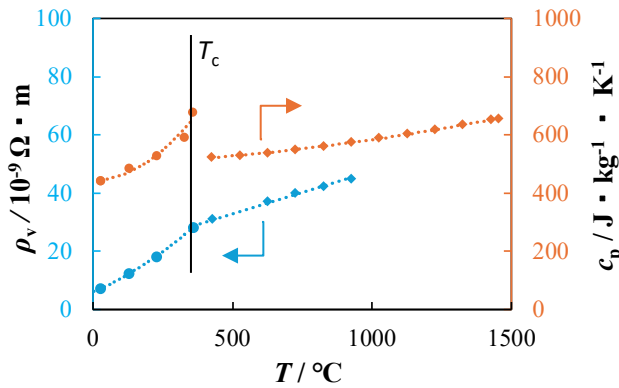


Figure 0-4 Physical properties of nickel

The current and temperature changes in the fusing wire were predicted using Equations (2.4-2)–(2.4-4). Here, A denotes the cross-sectional area, L denotes the length, T denotes the temperature, h denotes the specific enthalpy, c_p denotes the specific heat, I denotes the current flowing through the fusing wire, V denotes the voltage applied to the fusing wire, ρ denotes the density, and ρ_v denotes the electrical resistivity.

$$\rho AL \frac{d}{dt} h(T) = IV \quad (2.4-2)$$

$$h(T) = \int_{T_0}^T c_p(T) dT \quad (2.4-3)$$

$$I = \frac{A}{\rho_v(T)L} V \quad (2.4-4)$$

Figure 2.4-5 shows the experimental and calculation results indicating current, voltage, and temperature changes during the fusing process of the fusing wire. The fusing wire length L was set to a relatively long value of 154 mm, and an alternating-current voltage of 230 V was applied to enable sufficient focus on the melting process. Comparison with the experimental results showed that the calculation results well-reproduced the change in the current and the time required to reach fusing. In addition, the input energy supplied to the fusing wire was calculated from Equation (2.4-5) by integrating the current and voltage over time. The experimental value was 16.6 J, and the calculated value was 15.3 J, showing good agreement between the two.

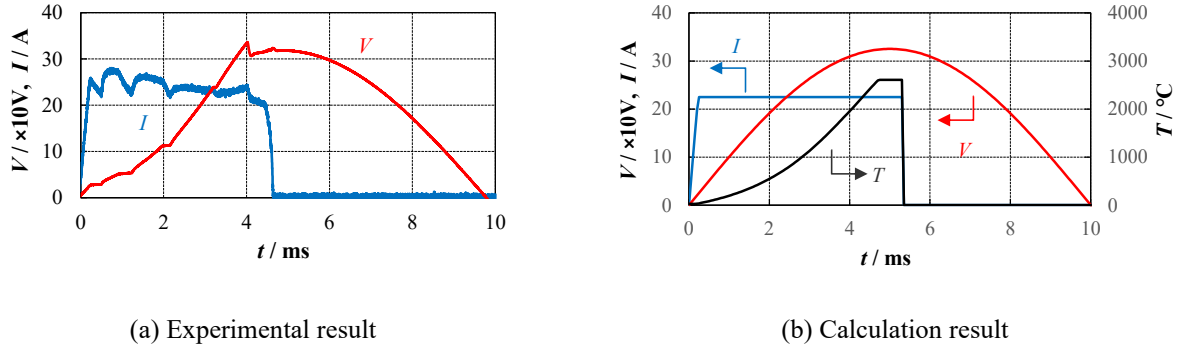


Figure 0-5 Results of the wire fusing test

$$E_{\text{fus}} = \int_0^{t_{\text{fus}}} IV dt \quad (2.4-5)$$

Figure 2.4-6 shows the experimental results for the energy required until fusing at different electrode distances, i.e., different fusing wire lengths. The horizontal axis represents the electrode distance, and the vertical axis represents the energy calculated using Equation (2.4-5). In addition, the energy required to completely melt the fusing wire, obtained from the volume and specific heat of the fusing wire, is shown for comparison. The results indicated that the energy required until the fusing wire fused was proportional to the fusing wire length and approximately agreed with the energy required to melt the wire completely. These results show that the energy consumed until fusion of the fusing wire can be predicted based on the physical properties of the fusing wire and the energy required to melt the wire completely. Notably, the electrical input energy during the fusing process is entirely consumed in changing the state of the fusing wire, and this energy is not necessarily supplied to the refrigerant under evaluation.

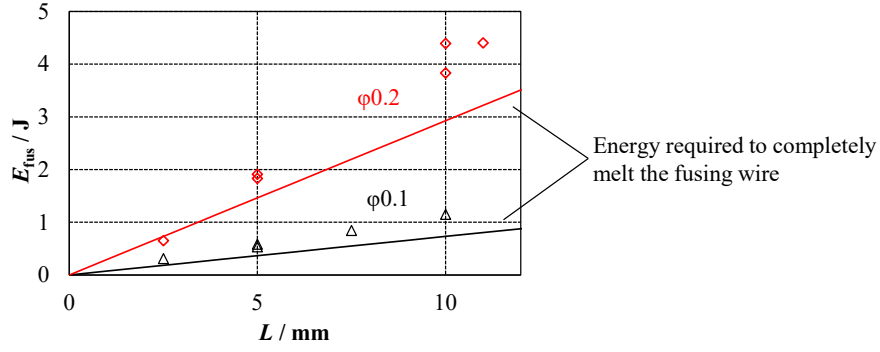


Figure 0-6 Relationship between the energy input and electrode distance

2.4.3 Evaluation of arc discharge

As described in the preceding section, in the fusing wire and discharge method, arc discharge occurs after the fusing wire fuses. The arc voltage (V_{arc}) is determined by the electrode geometry and the type and state of the gas. In addition, when a stabilized power supply is used, as in the present test method, the current and application time are set on the power supply side. The energy input by arc discharge (E_{arc}) is expressed by Equation (2.4-6), and, among the variables in this equation, the current (I) and application time (t_{arc}) are specified by the power supply. Therefore, if the arc voltage (V_{arc}) is known, the amount of input energy can be predicted and controlled. Here, the arc voltage under various conditions was investigated.

$$E_{arc} = \int_{t_{fus}}^{t_{arc}} V_{arc} I dt \quad (2.4-6)$$

Figure 2.4-7 shows the arc voltage when the electrode distance (L) was varied. The electrode distance is plotted on the horizontal axis, and the arc voltage is plotted on the vertical axis. Tests were conducted using R32 and N_2 (as well as air) at 0.1 and 0.7 MPa. A nickel wire with a diameter of 0.1 mm was used as the fusing wire. The arc voltage may vary somewhat depending on the experimental conditions, presumably owing to changes in arc behavior. In this study, the minimum voltage, corresponding to the case in which the arc takes the shortest path, was used as the representative value of the arc voltage.

In Figure 2.4-7, the arc voltage increased linearly with the electrode distance. The intercept was approximately 20 V and was almost identical under all experimental conditions. By contrast, the slope was greater for R32 than for N_2 and increased as the pressure became higher. In general, the arc voltage is expressed as the sum of the cathode–anode voltage drop (V_{A+C} in Figure 2.4-7) and the arc-column voltage drop. This indicates that the arc voltage (V_{arc}) can be expressed by Equation (2.4-7). Here, the first term represents the cathode–anode voltage drop and the second represents the arc-column voltage drop, which is proportional to the electrode distance. These results also show that the value of coefficient a depends on the type and state of the gas.

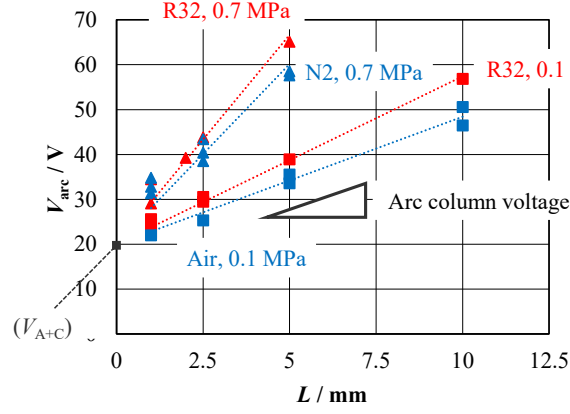


Figure 0-7 Relationship between the arc voltage and electrode distance

$$V_{arc} = V_{A+C} + a \cdot L \quad (2.4-7)$$

Figure 2.4-8 shows the arc voltage when the gas density was varied. The horizontal axis represents gas density, and the vertical axis represents arc voltage. The electrode distance was 1 mm in all cases, and a nickel wire with a diameter of 0.1 mm was used as the fusing wire. Experimental results obtained at different temperatures and pressures were organized in terms of gas density. The arc voltage increased as the gas density increased. The results for R32 also showed that the temperature dependence was small under the present experimental conditions.

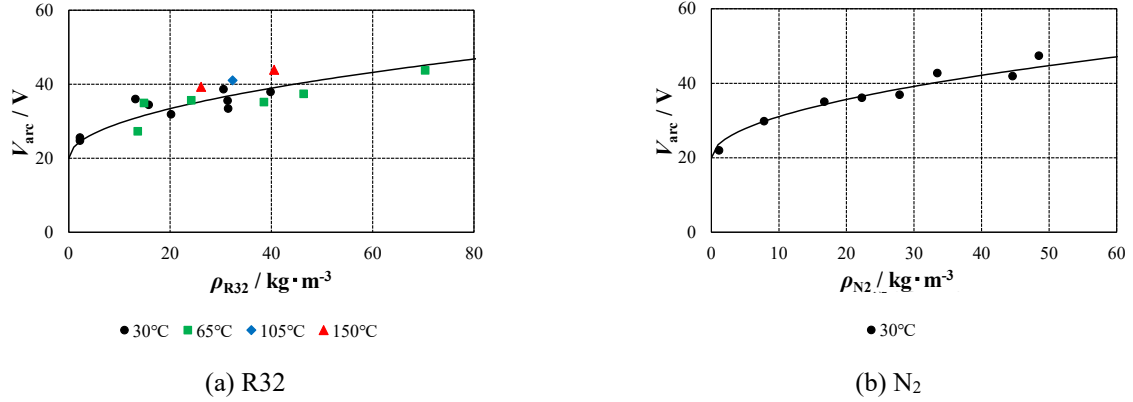


Figure 0-8 Relationship between gas density and arc voltage

Based on the above results, the arc discharge voltage (V_{arc}) can be predicted and controlled using Equation (2.4-8), which includes the cathode–anode voltage drop (V_{A+C}), electrode distance (L), gas density (ρ_{gas}), and parameters determined by the gas species ($\Delta V, \beta$). Table 2.4-1 outlines the values of each parameter obtained under the test conditions. Suga *et al.* (1988) investigated the arc voltage in a high-pressure argon atmosphere and reported that the arc-column voltage drop is proportional to a power function of the product of the electrode distance and gas pressure. A similar tendency was observed in the present study, demonstrating that the arc voltage and the input energy in the fusing wire and discharge method can be predicted and controlled using Equation (2.4-8) and the values in Table 2.4-1.

$$V_{arc} = V_{A+C} + \Delta V \cdot L \cdot (\rho_{gas})^{\beta} \quad (2.4-8)$$

Table 0-1 Constants for predicting the arc voltage ($L = 1$ mm)

Gas	V_{A+C}	ΔV	β
	V	$V \cdot \text{mm}^{-1} \cdot (\text{kg} \cdot \text{m}^{-3})^{-\beta}$	-
R32	20	3.1	0.5
N ₂	20	3.5	0.5

Figure 2.4-9 shows a comparison in which the material of the fusing wire was varied. The experimental conditions were N₂, 0.1 MPa, room temperature, and a current limit of 189 A. The comparison of nickel (Ni) and molybdenum (Mo) showed that the maximum electrode distance at which the arc discharge formed differed between the materials; discharge was possible with the Mo wire over a longer electrode distance than with the Ni wire. However, no effect of the fusing wire material on the input energy during arc discharge was observed.

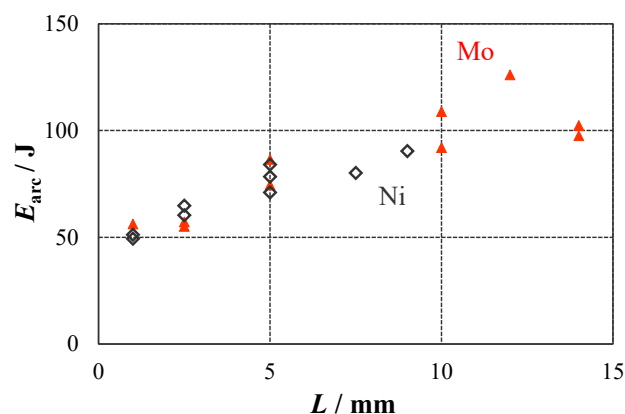


Figure 0-9 Comparison of fusing wire material

These results showed that the arc voltage and input energy can be predicted based on the electrode distance and gas density. In particular, when the electrode distance increases, the arc voltage also increases, which promotes arc instability and makes discharge formation more difficult. From this perspective, a shorter electrode distance is preferable. For the fusing wire, reducing the wire diameter can decrease the energy consumed during the fusing process, thereby enabling a more accurate evaluation of the energy supplied to the refrigerant. However, operability must also be considered in the practical test method. Based on the above, for the purpose of evaluating refrigerant self-decomposition reactions, an electrode distance of 1 mm and a fusing wire diameter of 0.1 mm were judged to be appropriate conditions. Table 2.4-2 shows the test conditions judged to be appropriate based on the present test results, together with the relevant conditions in the TDG method and EN 1839.

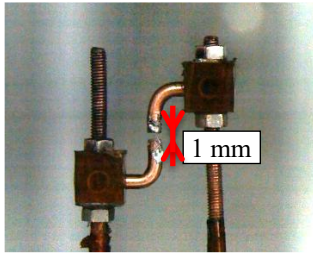
Table 0-2 Proposal conditions for self-decomposition reaction evaluation and comparison with existing standards

	Method for self-decomposition reaction evaluation	TDG	EN 1839
Diameter of electrodes	3 mm	-	-
Distance between electrodes	1 mm	3–6 mm	4–6 mm
Fusing wire material	Ni	Ni	NiCr
Fusing wire diameter	0.1 mm	0.12 mm	0.05–0.2 mm

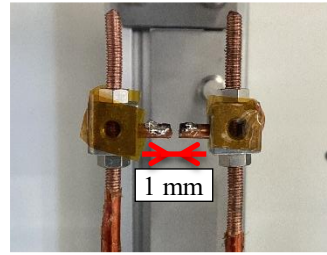
2.4.4 Discussion on the instability of arc discharge

When energy is supplied using an arc between electrodes, the behavior of the arc discharge may become unstable during energization. In such cases, the arc length may expand or contract as the arc path bends, or the contact point between the arc discharge and the electrode, namely the arc spot, may shift. When this occurs, the length corresponding to L in Equation (2.4-8) becomes longer than the interelectrode distance, causing the arc voltage to increase and thereby changing the input energy. Therefore, the possibility of suppressing arc discharge fluctuations by modifying the electrode geometry was investigated (Ito *et al.*, 2025).

The principal forces influencing the arc discharge behavior include buoyancy caused by heating the gas (Handa, 1972) and the electromagnetic force acting on the electrons, namely the Lorentz force. Among these, buoyancy acts in the direction that causes the arc to detach from the space between the electrodes; therefore, an electrode geometry that suppresses this effect was examined. In this study, electrodes in which the arc orientation was vertical (Figure 2.4-10(a)) were fabricated and compared with horizontal electrodes (Figure 2.4-10(b)).



(a) Vertical electrodes



(b) Horizontal electrodes

Figure 0-10 Electrodes for evaluation of arc discharge stability

As in the tests described in relation to Figure 2.4-7, discharge tests were conducted using R32 while varying the refrigerant density. Here, the voltage increase ratio (V_{increase}), defined by Equation (2.4-9), was evaluated as an index of stability.

$$V_{\text{increase}} = \frac{V_{\text{arc,avg}} - V_{\text{arc,min}}}{V_{\text{arc,min}}} \quad (2.4-9)$$

Here, $V_{\text{arc,min}}$ is the minimum voltage during arc discharge, and $V_{\text{arc,avg}}$ is the average voltage during arc discharge. A larger voltage increase ratio indicates greater arc instability.

Figure 2.4-11 shows the experimental results. Compared with the horizontal electrodes, the vertical electrodes exhibited a smaller voltage increase ratio, indicating the formation of a stable arc discharge. If arc discharge instability becomes an issue in establishing the test method in the future, the above considerations will be considered.

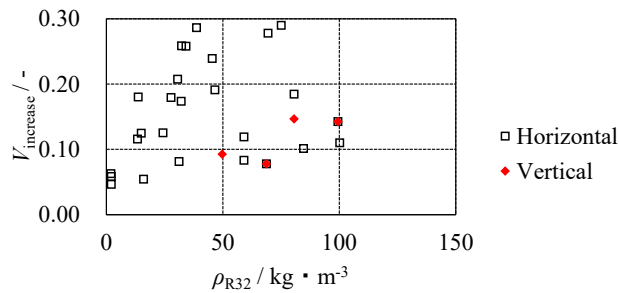


Figure 0-11 Comparison of the voltage increase ratio by electrode structure

2.5 Interlaboratory comparison test

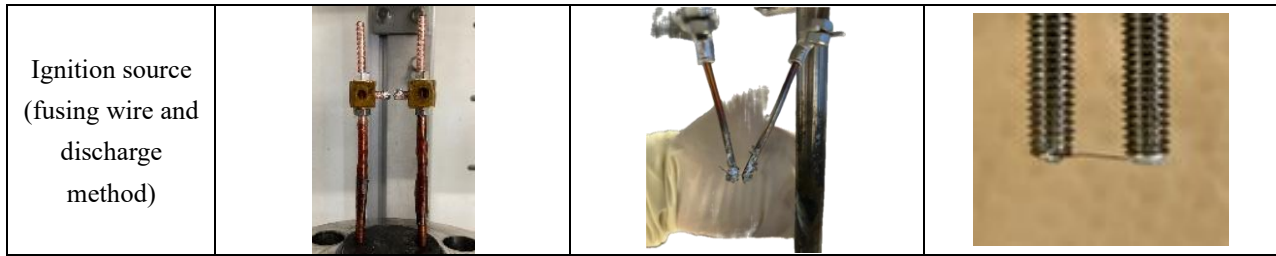
In the preceding section, the relationships between each parameter in the fusing wire and discharge method and the input energy supplied to the refrigerant were investigated, and appropriate conditions for a method to evaluate refrigerant self-decomposition reactions were narrowed down. This section describes the results of interlaboratory comparison (ILC) tests conducted by three organizations in Safety Gr.—CRIEPI, AGC, and DAIKIN—to verify the validity of this test method. In these tests, the three organizations conducted experiments under identical conditions using the same refrigerant, and the reaction boundary pressures (RBPs) obtained were compared (Higashi *et al.*, 2025b).

2.5.1 Test apparatus

Table 2.5-1 shows images of the test apparatuses used by the three organizations, the dimensions and internal volumes of the reaction vessels, and the images of the ignition electrodes. For CRIEPI, the apparatus shown in Figure 2.3-1 was used. In all apparatuses, the fusing wire and discharge method shown in Figures 2.3-3 and 2.3-4 was employed. Although differences were observed in the dimensions and external shapes of the apparatuses, their basic structures were all similar to the configuration shown in Figure 2.3-1.

Table 0-1 Experimental apparatus for interlaboratory comparison test

	CRIEPI	AGC	DAIKIN
Overview			
Size of the pressure vessel (inner diameter, height, volume)	φ40 mm, 250 mm, 314 cm ³	φ72 mm, 171.3 mm, 650 cm ³	φ82.5 mm, 95 mm, 500 cm ³



2.5.2 Test conditions

Table 2.5-2 shows the test conditions. R1132a ($\text{CH}_2=\text{CF}_2$), which is a candidate low-GWP refrigerant alternative to low-temperature refrigerants such as R23, was used as the target refrigerant (Qin *et al.*, 2021). R1132a is an ethylene-based refrigerant, as are HFO-1123 and R1132(E), and it has been reported to undergo self-decomposition reactions (Lisochkin *et al.*, 2006). The test temperature was set to 150 °C according to previous studies assuming compressor failure, and the input energy (E) was set to 25 J. The input energy was calculated by integrating the product of current and voltage over time using Equation (2.5-1). The interelectrode distance was set to 1 mm. A nickel wire with a diameter of 0.1 mm was used as the fusing wire. For each condition, the allowable tolerances shown in Table 2.5-2 were specified, and results that did not satisfy these tolerances were excluded from the analysis.

Table 0-2 Experimental Conditions	
Parameter	Value
Refrigerant	R1132a
Initial temperature (T_0)	150 ± 5 °C
Initial pressure (P_0)	(Varied)
Input energy (E)	25 ± 5 J
Gap between electrodes	1 ± 0.1 mm
Fusing wire material	Nickel
Fusing wire diameter	0.1 mm

$$E = \int_0^t IV dt \quad (2.5-1)$$

2.5.3 Test procedure

In each test, after the refrigerant was charged, the pressure vessel was heated and adjusted to the prescribed temperature and pressure. Energy was then supplied using the ignition source installed inside the vessel. When the reaction propagated, the temperature and pressure inside the reaction vessel increased. At the same initial pressure (P_0), up to three tests were conducted, and the presence or absence of reaction propagation under each condition was judged as follows:

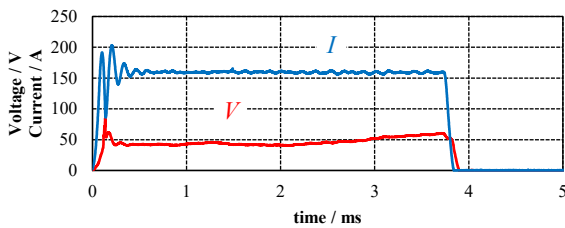
- Reaction propagation present: If the pressure increased by more than 30% of the initial pressure in at least one test, the condition was judged as “reaction propagation present.”
- Reaction propagation absent: If the pressure increase was 30% or less of the initial pressure in all tests, the condition was judged as “reaction propagation absent.”

Among the test results judged as “reaction propagation present,” the minimum measured initial pressure was defined

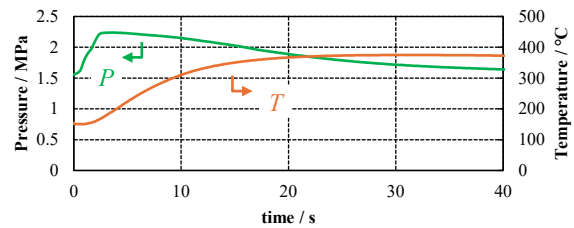
as the upper bound pressure (UBP). Among the test results judged as “reaction propagation absent,” the condition with the maximum average measured initial pressure was defined as the lower bound pressure (LBP). The tests were repeated while varying the initial pressure. In addition, the average of the UBP and LBP was defined as the RBP.

2.5.4 Test results

Figure 2.5-1 shows the changes in the current and voltage of the ignition source (Figure 2.5-1(a)) and the changes in temperature and pressure inside the reaction vessel (Figure 2.5-1(b)) under a condition in which the reaction propagated (initial pressure: 1.56 MPa). As shown in Figure 2.5-1(a), the current was maintained nearly constant around the power supply setting value, with a maximum of 160 A. The arc voltage was determined based on the physical properties of the refrigerant and the pressure and temperature conditions during the test and was approximately 50 V under this condition. The input energy was controlled to 25 J by adjusting the discharge duration. As shown in Figure 2.5-1(b), the pressure increased to a maximum of 2.24 MPa and then gradually decreased. The temperature increased to approximately 400 °C. The ratio of the maximum pressure to the initial pressure, namely the pressure ratio, was 1.44, exceeding 1.3; therefore, this condition was judged as “reaction propagation present.”



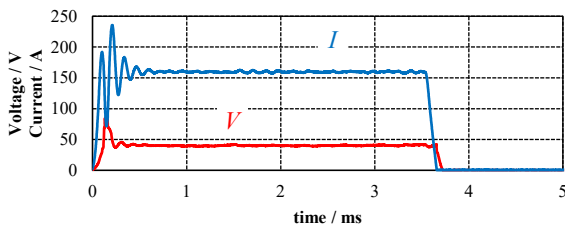
(a) Change in voltage and current



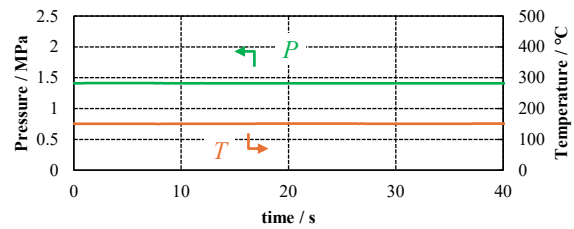
(b) Change in pressure and temperature

Figure 0-1 Results under the “reaction propagation” condition ($P_0 = 1.56$ MPa)

Figure 2.5-2 shows the changes in the current and voltage of the ignition source (Figure 2.5-2(a)) and the changes in temperature and pressure inside the reaction vessel (Figure 2.5-2(b)) under a condition in which the reaction did not propagate (initial pressure: 1.41 MPa). As shown in Figure 2.5-2(b), the pressure and temperature remained almost constant during the test, and the pressure ratio was 1.00. Therefore, this condition was judged as “reaction propagation absent.”



(a) Change in voltage and current



(b) Change in pressure and temperature

Figure 0-2 Results under the “no reaction propagation” condition ($P_0 = 1.41$ MPa)

Figure 2.5-3 shows the test results based on the measurement data obtained by CRIEPI. The horizontal axis represents the input energy, and the vertical axis represents the initial pressure. Open circles indicate “reaction propagation absent” conditions, whereas crosses indicate “reaction propagation present” conditions. The maximum and minimum input energies in this test were 27.2 J and 22.2 J, respectively. Both values were within the target range of 25 ± 5 J, confirming

that the input energy can be controlled with high reproducibility by the fusing wire and discharge method. Based on these results, the reaction boundary pressures were determined as follows:

- LBP = 1.41 MPa
- UBP = 1.56 MPa
- RBP = 1.48 MPa.

Figure 2.5-4 shows a comparison of the results obtained by the three organizations. For each organization, the UBP, LBP, and RBP are shown, and measurement uncertainties based on the pressure gauge accuracy are also indicated for the UBP and LBP. The RBP values obtained by CRIEPI, AGC, and DAIKIN were 1.48 MPa, 1.28 MPa, and 1.37 MPa, respectively, with an average value of 1.38 MPa. Considering the range between the UBP and LBP, the results from all three organizations were within $\pm 5\%$ of the average value. These results indicate that the test method and test conditions described in this paper provide consistent results across different testing organizations.

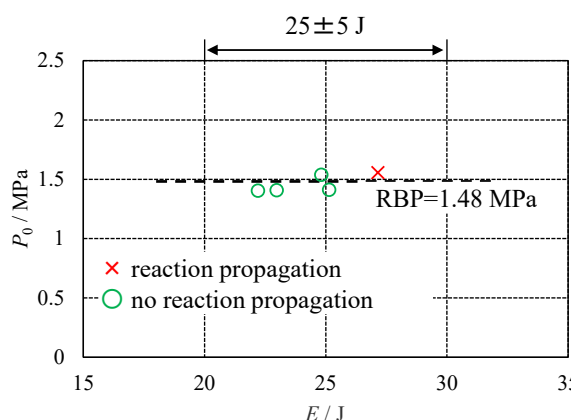


Figure 0-3 Experimental results
(obtained by CRIEPI)

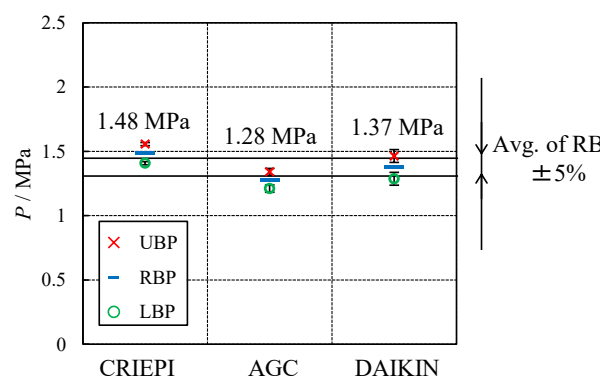


Figure 0-4 Comparison of the results obtained by three
organizations

*: UBP: Upper bound pressure; RBP: Reaction
boundary pressure; LBP: Lower bound pressure.

These results demonstrated that the fusing wire and discharge method is valid for evaluating refrigerant self-decomposition reactions. Based on these results, proposals are currently being made regarding the outline of the ISO 817 standard revision, the test method, and the principal test conditions. However, items that have not yet been fully specified in previous investigations, such as the amount of input energy, input duration, and vessel volume, may also affect the test results. Further studies on international standardization will continue, including evaluating the dependence on these parameters.

2.6 Summary

For evaluating the self-decomposition reactions of next-generation refrigerants, an evaluation method is currently being developed to provide a revision of ISO 817. Based on comparisons of various ignition methods, the fusing wire and discharge method was developed as an evaluation method with high reproducibility and simplicity for international standardization, and the effects of various parameters on the input energy were evaluated. Interlaboratory comparison tests were conducted to assess the validity of this evaluation method. Based on these findings, proposals are currently being made regarding the outline of the ISO 817 standard revision, the test method, and the principal test conditions. In the future, the developed evaluation method will be used to evaluate the self-decomposition reactions and safety of next-

generation low-GWP refrigerants, to narrow down promising refrigerant compositions, and to conduct risk assessments related to self-decomposition reactions under assumed practical-use conditions. By standardizing the self-decomposition reaction evaluation and risk assessment, efforts will continue to contribute to the development of an environment and information dissemination that enable safe usage of next-generation low-GWP refrigerants.

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3. Development of Self-Decomposition Reaction Evaluation Methods and Study of HFO-1123 Refrigerant Mixtures (AGC)

3.1 Background and objectives of research and development

3.1.1 Social demand for international standardization of self-decomposition reaction evaluation methods

The field of refrigeration and air conditioning has recently experienced increased concern over environmental issues, including global warming, and environmental regulations have become progressively more stringent, thereby driving growing demand for a transition to more environmentally benign next-generation refrigerants. The prevention of global warming is driving a shift from HFC refrigerants, which have a high warming effect, to HFO and natural refrigerants with lower global warming impact; however, each type has flammability, toxicity or chemical instability challenges.

Among HFO refrigerants, HFO-1123 and R1132(E), which are attracting attention as next-generation refrigerants, share the common feature of possessing a carbon–carbon double bond. As such, they are chemically unstable. As shown in Figure 3.1-1 (a) and (b), when such substances are used in practice, the interior may reach a high-temperature and high-pressure state if a malfunction occurs inside a refrigerant compressor, and a self-decomposition reaction may occur if energy is forcibly supplied from outside simultaneously (for example, a layer short); once certain conditions (temperature, pressure, and input energy) are satisfied, this reaction propagates chainwise to the surroundings.

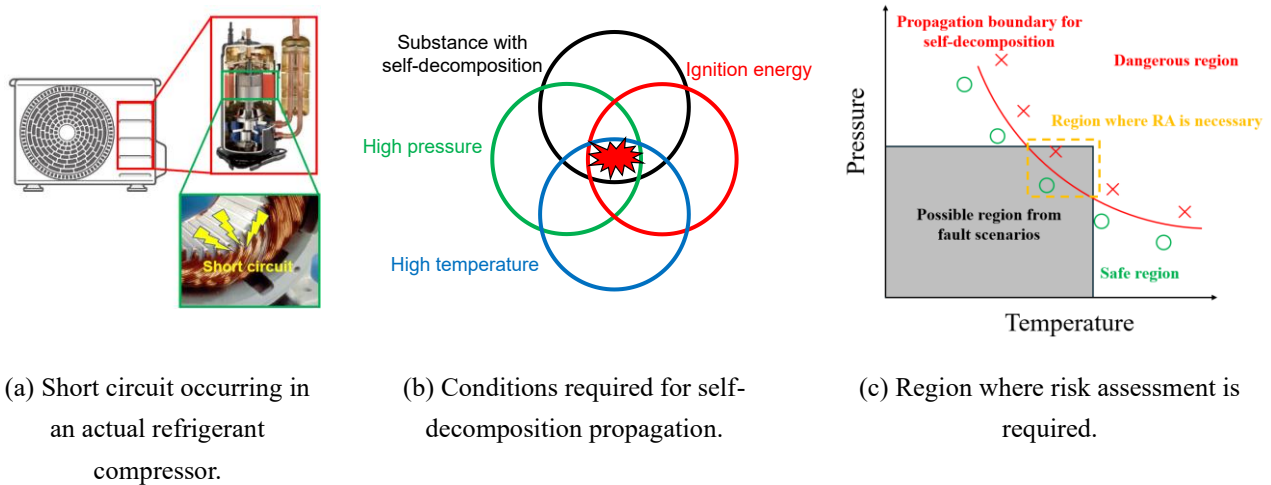
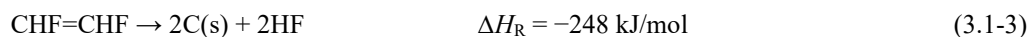
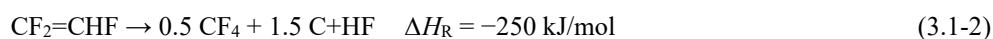


Figure 0-1 Risk assessment of self-decomposition propagation

Self-decomposition reactions are not rare phenomena; they are known to be caused by TFE (tetrafluoroethylene, $\text{CF}_2=\text{CF}_2$), HFO-1123 (trifluoroethylene, $\text{CF}_2=\text{CHF}$), and R1132E (trans-1,2-difluoroethylene, trans- $\text{CHF}=\text{CHF}$), and the self-decomposition reactions of these substances are shown in Equations (3.1-1)–(3.1-3). If the above reactions propagate inside an actual refrigerant compressor, the temperature and pressure may increase and result in accidents. Consequently, ensuring safety through risk assessment is crucial for disseminating HFO refrigerants facing such challenges as next-generation refrigerants.



As shown in Figure 3.1-1 (c), when an abnormality occurs, the maximum temperature and pressure ranges reached inside an actual refrigerant compressor are compared with the range in which self-decomposition reactions propagate; an overlapping region is risky owing to self-decomposition reactions, and risk assessment must be conducted to ensure safety. Risk evaluation is performed by assessing the probability of occurrence and the severity of harm using a fault tree analysis (FTA). However, regarding the methods for investigating the conditions under which self-decomposition reactions propagate, evaluation methods have not yet been established, and there is concern that different results may be obtained owing to the different test devices and methods used by different companies and research institutions. Therefore, the international standardization of evaluation methods is indispensable for achieving the goal of widespread adoption as next-generation refrigerants. Accordingly, in this study, we acquired fundamental data supporting the validity of evaluation methods that are indispensable for the international standardization of self-decomposition reaction evaluation methods.

3.1.2 Importance of developing ignition methods for international standardization

In the previous subsection, the importance of the international standardization of self-decomposition reaction evaluation methods for the dissemination of HFO refrigerants was described; in this subsection, the importance of ignition methods within the evaluation methods is explained. Evaluation methods comprise the test equipment, ignition method, test procedure, and evaluation criteria, among which the ignition method is the most critical. Energy has been supplied using various ignition methods, such as the fusing wire, hot-spot, and discharge methods, to simulate the process for initiating self-decomposition reactions by forcibly starting the reaction. These ignition methods were developed by assuming different phenomena as triggering factors for self-decomposition reactions. The fusing wire method simulates the process in which enamel wire inside a refrigerant compressor is fused under high temperature; the hot-spot method simulates the wall surface of a vessel heated to medium or high temperature; and the discharge method was developed to simulate the layer-short phenomenon that occurs between enamel wires; therefore, the phenomena simulated by these methods differ. During risk assessment, among the different ignition methods, evaluation must be conducted using the method that simulates the triggering factor presenting the highest risk considering the probability of occurrence and hazard severity. If the ignition method selected is inappropriate, the simulated phenomena differ, and different propagation ranges for self-decomposition reactions may be obtained, which would make proper risk assessment impossible. Among the various triggering factors, the propagation risk of self-decomposition reactions owing to the layer-short phenomenon, which is a discharge phenomenon, is considered the highest; accordingly, we concentrated on the development of discharge methods. Within Safety Gr., Suwa University of Science is investigating the discharge patterns of actual discharge phenomena occurring in real equipment. In the present study, we ensured appropriate risk assessment by developing a discharge method capable of simulating the characteristics of discharge phenomena that can occur in equipment, as elucidated by Suwa University of Science.

Previous studies (Goto *et al.*, 2024; Otsuka *et al.*, 2018a; Otsuka *et al.*, 2018b; Zhang *et al.*, 2023) have developed a discharge method based on dielectric breakdown using needle electrodes and a discharge method using electrodes with contact points; however, the former cannot be used under high-pressure conditions owing to Paschen's law, and the latter has problems related to the reproducibility and success rate of discharge energy. Moreover, although the above discharge methods simulate the layer-short phenomenon well, they do not satisfy the simplicity and reproducibility required for an international standard. Based on TDG, an international standard for evaluating the safety of transported materials, Safety Gr. developed the fusing wire and discharge method, which simultaneously satisfies the reproducibility of the discharge

3.2 Issues with existing ignition methods and consideration of improvements

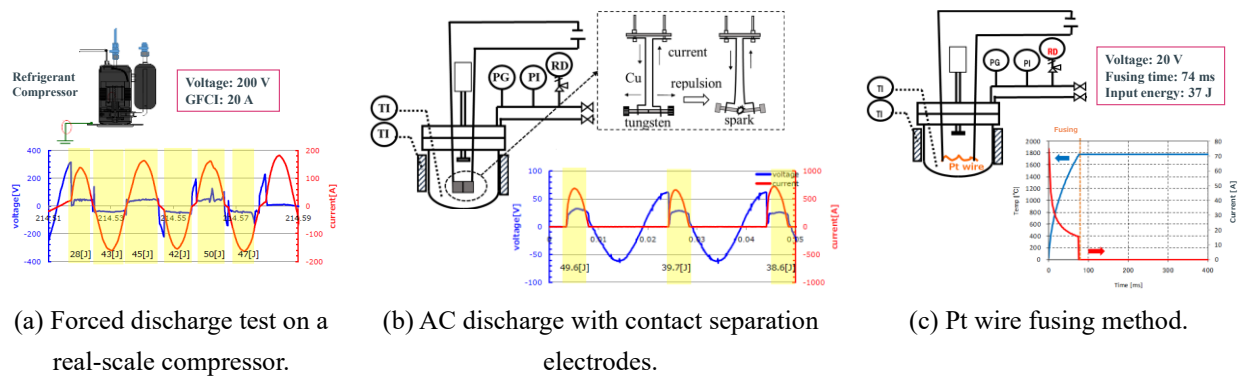


Figure 10 consists of two scatter plots, (a) and (b), showing Spark energy (J) on the y-axis (ranging from 0.0 to 80.0) versus Test number on the x-axis. Both plots include a legend indicating that open circles represent 'not disproportionated' and filled circles represent 'disproportionated'.

(a) 100 °C and 0.5 MPa: The x-axis ranges from 0 to 100. The plot shows a wide distribution of spark energy values. Most data points are open circles (not disproportionated), with a few filled circles (disproportionated) appearing at higher test numbers (around 50, 70, 75, and 95). A blue box highlights the conditions '100 °C, 0.5 MPa'.

(b) 100 °C and 1.0 MPa: The x-axis ranges from 0 to 160. The plot shows a similar distribution of spark energy values. There are more filled circles (disproportionated) compared to plot (a), particularly between test numbers 50 and 140. A blue box highlights the conditions '100 °C, 1 MPa'.

25

The current and voltage waveforms of the AC discharge shown in Figure 3.2-1 (a), (b) indicate that arc discharge does not occur unless the current and voltage exceed certain thresholds. Switching from AC to DC power supply prevents arc extinction caused by decreases in voltage and current, thereby resolving the instability described above; however, the issue of arc-generation success rate remains. As shown in Figure 3.2-3, the arc-generation process for electrodes with contact points can be divided into the following steps:

- ① When voltage is applied, the electrodes are heated by Joule heating.
- ② Thermionic electrons are emitted, and metal vapor is also generated.
- ③ Plasma is generated in the gap between the electrodes and in the surrounding region.
- ④ The plasma body flows along the electric field and an arc is generated.
- ⑤ The interelectrode distance increases owing to the gas expansion caused by high temperature in the gap and the electromagnetic repulsive force between the parallel electrode plates.
- ⑥ The arc length changes, causing the arc voltage to change.

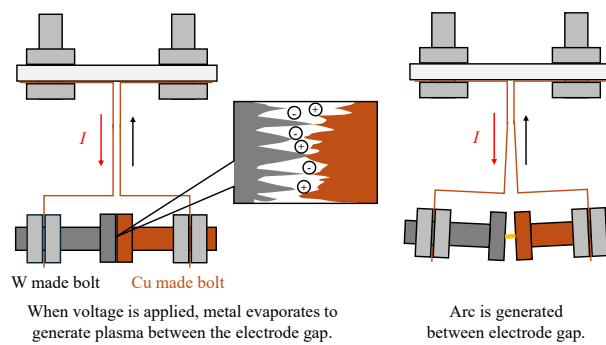
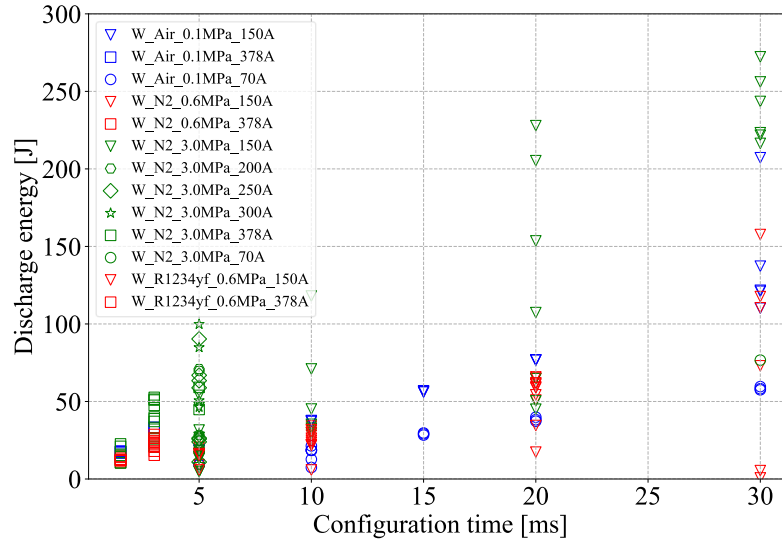
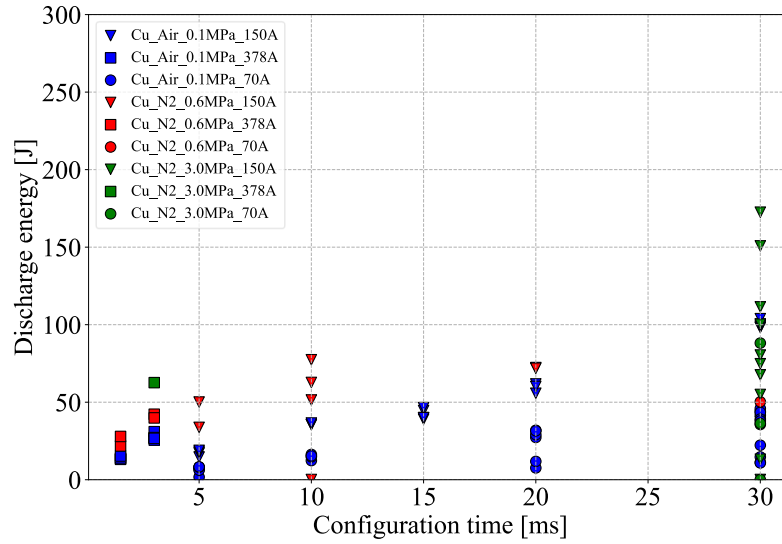


Figure 0-3 Mechanism of contact separation electrodes

The reason behind the instability of arc generation with the existing electrodes (Figure 3.2-4 (a)) lies in Step ② and is attributable to the delayed generation of metal vapor caused by tungsten usage, which has a high melting point. As a countermeasure, the electrode material was changed to copper, which has a lower melting point, and it was confirmed that the arc-generation rate improved markedly. However, a new problem emerged: the electrodes became more prone to welding, and, as shown in Figure 3.2-4 (b), the arc did not continue for the intended application time, causing the discharge energy to fall below the set value. These issues were addressed by improving the electrode structure to a hybrid configuration that utilizes the material characteristics of both tungsten, which is resistant to welding, and copper, which readily initiates discharge. By using copper for one electrode and tungsten for the other, it became possible to develop an electrode structure that simultaneously achieves stable arc generation and continuation of the arc for the intended application time without electrode welding.



(a) W electrodes



(b) Cu electrodes

Figure 0-4 Low reproducibility of discharge energy

Because the characteristics of arc discharge closely resemble those of a short circuit, in direct-current discharge, as shown in Figure 3.2-5 (a), the current is limited by the current-limiter setting of the regulated power supply, whereas the arc voltage depends on the electrode material and becomes constant once a stable state is reached. In alternating-current discharge, as shown in Figure 3.2-5 (b), the current and voltage vary with time, and arc formation occurs only above a threshold value, resulting in the appearance of an arc-voltage component. Because both the current and voltage return to 0 V every half cycle, the arc cannot persist beyond a half cycle. Uncertainty in both the duration within each half cycle and the total number of discharge events contributes to the low reproducibility of the discharge energy described above. By contrast, in the direct-current discharge method, the voltage remains constant, allowing the current-limiter setting to be adjusted to reproduce the energy density of discharge patterns observed in actual equipment. Moreover, because the energy density remains constant, the total energy can be quantitatively controlled through the application time.

Accordingly, this study prioritized the reproducibility of actual equipment phenomena and succeeded in developing a discharge method capable of reproducing discharge patterns over a range of energy densities and total energies. The reproducibility of discharge and the quantitative controllability of the input energy were evaluated in air and in high-pressure N₂ and R32 atmospheres. As shown in Figure 3.2-6, excellent reproducibility and quantitative control of the input energy were achieved in a high-pressure R32 atmosphere close to the actual operating environment, even at different energy densities. By contrast, arc-voltage fluctuations were more pronounced in an N₂ atmosphere, and the uncertainty of the discharge energy tended to increase.

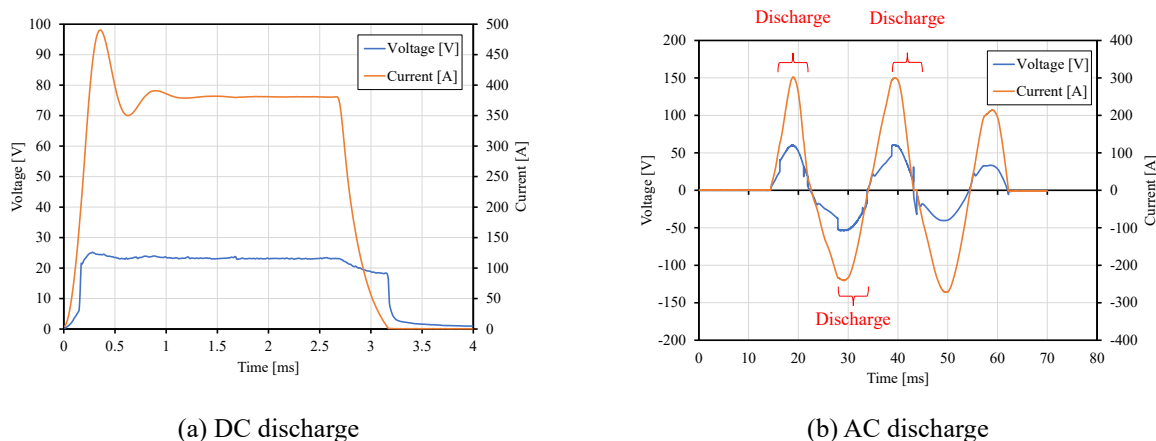


Figure 0-5 Typical current and voltage waveforms for DC and AC discharge

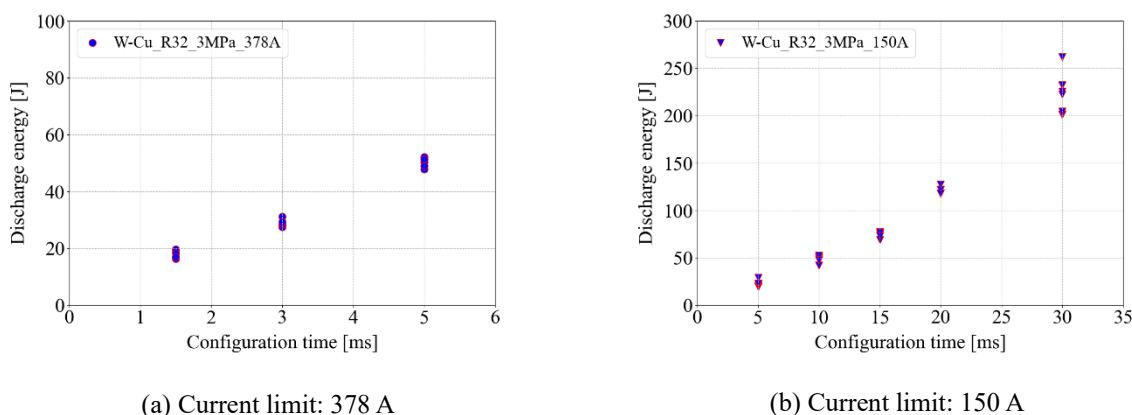


Figure 0-6 Discharge energy quantification at 3.0 MPa R32 under different current limiters

3.3 Evaluation of the effects of various parameters on the discharge behavior of the fusing wire and discharge method

When international standardization of self-decomposition reaction evaluation methods is pursued, it is necessary to select an appropriate ignition method. From the viewpoint of simultaneously satisfying the simplicity of testing and the representativeness of actual equipment phenomena, Safety Gr. proposed the fusing-wire and discharge method, developed based on the TDG method, as the ignition method for the evaluation method to be standardized internationally. A schematic of the fusing wire and discharge method is shown in Figure 3.3-1. In this method, the metal fine wire connecting the electrode rods is fused after current is applied, and an arc is generated at the location of the wire. Details of the evaluation method for self-decomposition reactions other than the ignition method are omitted here.

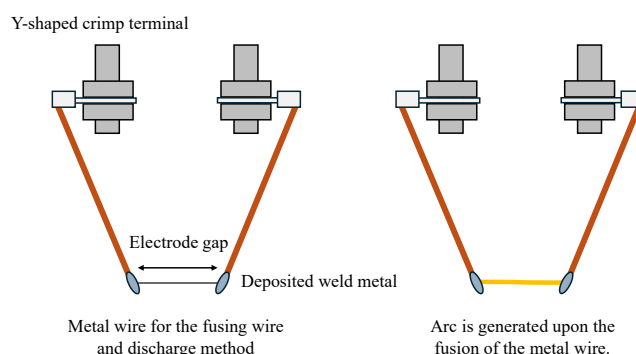


Figure 0-1 Electrodes for the fusing wire and discharge method

In order to internationally standardize an evaluation method that uses the fusing wire and discharge method as the ignition method, it is necessary to investigate the effects of fundamental parameters and to confirm consistency through interlaboratory comparison tests using a standard substance. Using this approach, the same results are obtained even when tests are conducted by different organizations. In this section, the effects of various parameters on the discharge behavior of the fusing wire and discharge method were investigated. These parameters include the electrode gap of the electrodes, the metal species and wire diameter of the metal fine wire, and the gas species and pressure of the discharge atmosphere.

In this study, test data providing the basis for international standardization of the evaluation method were acquired using the experimental apparatus shown in Figure 3.3-2. The apparatus mainly comprised a regulated power supply (NF Co. DP120RS), a pressure vessel made of Inconel with a design temperature and pressure of 390 °C and 45 MPa, respectively, pressure gauges PI and PG, thermocouples, and a rupture disk. Stainless-steel electrode rods were installed inside the pressure vessel, and by connecting various electrode structures, the effects of the fusing wire and discharge method parameters and the ignition performance of different electrode structures were evaluated.

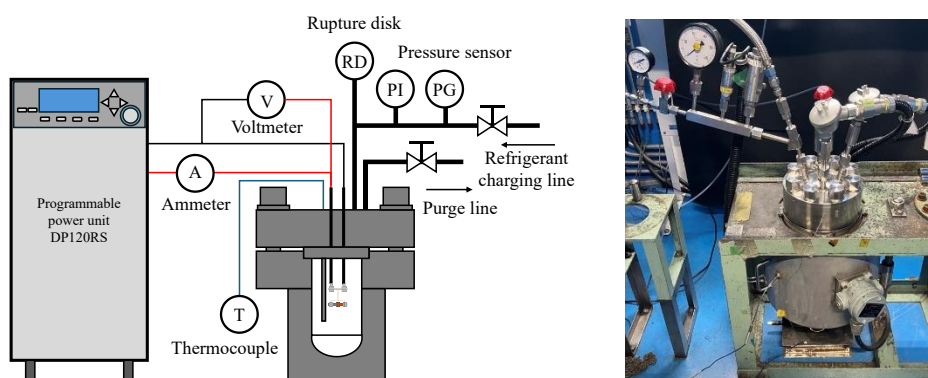


Figure 0-2 Schematic of the experimental apparatus

3.3.1 Effects of the electrode gap, metal species, and wire diameter of the metal fine wire

An ignition method is required to satisfy both the reproducibility and quantitative controllability of the discharge energy. The electrode gap affects the arc voltage, which depends on the arc length, and the maximum pressure at which discharge is possible according to Paschen's law; therefore, the effect of electrode gap on discharge behavior was investigated. In addition, because the present ignition method bridges the electrodes with a metal fine wire, the effects of the metal species and wire diameter used were also examined.

Figure 3.3-3 shows the results of an initial investigation conducted in air on the effects of the arc voltage, electrode gap, and wire diameter. Because AGC's contact separation electrodes have a contact point and the electrode gap can be regarded as infinitesimally close to 0 mm, it was found that the initial arc voltage increases in proportion to the electrode gap and exhibits an intercept that depends on the first ionization potential of the electrode material. The slope of the increase in arc voltage with electrode gap differed depending on the wire diameter.

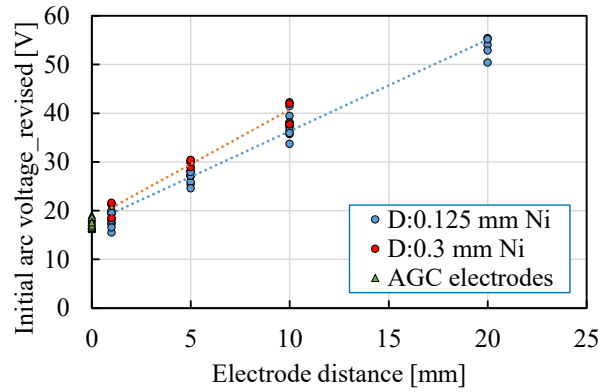


Figure 0-3 Relationship between the initial arc voltage and electrode distance

A typical example of the results obtained in investigating the effect of the wire diameter of the metal fine wire on the discharge behavior is shown in Figure 3.3-4. When the wire diameter of the Ni fine wire was changed from $\phi 0.125$ mm to $\phi 0.3$ mm, a substantial lag was observed from the start of current application until the metal wire fused and an arc was generated. As the wire diameter increases, the Joule heat required to generate the metal vapor indispensable for plasma formation through fuse breakage increases in proportion to the square of the wire diameter ratio; this is considered the reason for the lag until arc generation increased markedly.

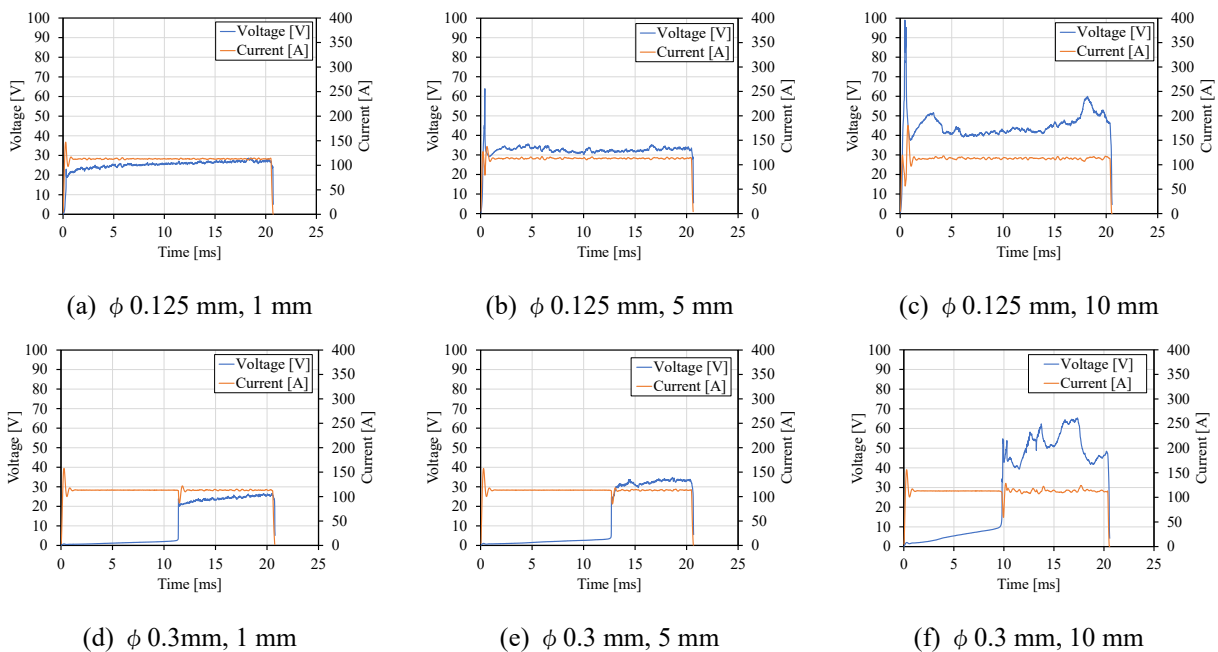
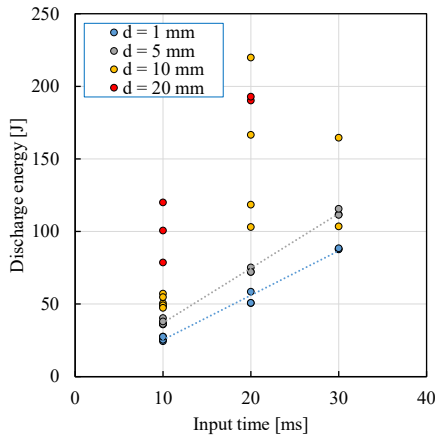
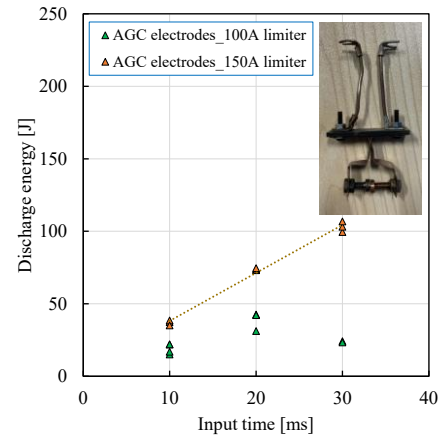


Figure 0-4 Influence of the metal wire diameter

The reproducibility of the discharge energy when the electrode gap was varied was also investigated. As shown in Figure 3.3-5(a), under conditions where the electrode gap exceeded 5 mm, the uncertainty in discharge energy increased, and quantitative control by voltage application time was no longer possible. In addition, as shown in Figure 3.3-5(b), comparison with the results for direct-current discharge using AGC's improved contact separation electrodes indicated that the result for a 5 mm electrode gap in the fusing wire and discharge method is close to the behavior observed when the current limiter is 150 A in the case of contact separation electrodes. When contact separation electrodes are used and the current limiter is 100 A, a phenomenon was also observed in which stochastic electrode welding causes the actual discharge duration to become much shorter than the voltage application time, resulting in reduced discharge energy.



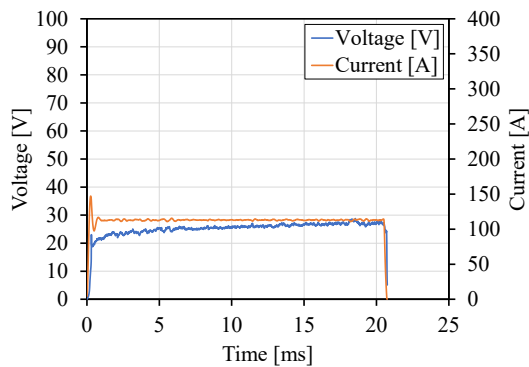
(a) Fusing wire and discharge method.



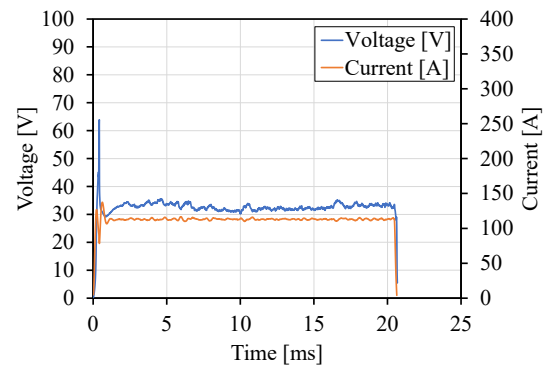
(b) DC discharge method with contact separation electrodes

Figure 0-5 Relationship between the input energy and time

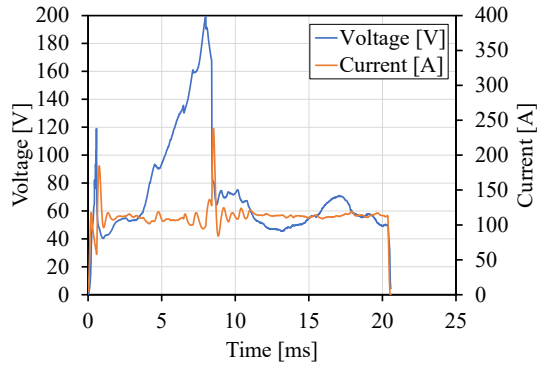
Figure 3.3-6 presents the results of an investigation into the reason behind the deterioration of the quantitative controllability of the discharge energy as the electrode gap increases, as shown in Figure 3.3-5 (a). From these results, we found that the increase in arc voltage and variations in the actual arc duration are behind the fluctuations in discharge energy.



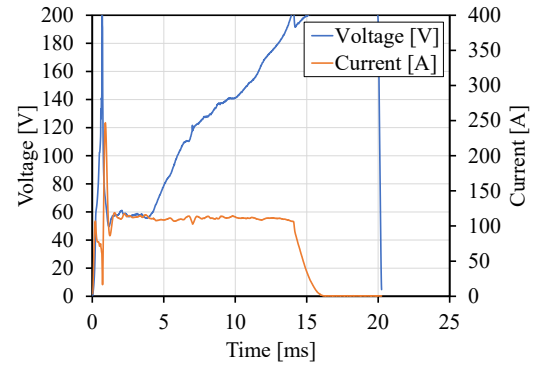
(a) 1 mm



(b) 5 mm



(c) 10 mm



(d) 20 mm

Figure 0-6 Change in arc voltage when the electrode distance increases (ϕ 0.125 mm)

Figure 3.3-7 shows the results obtained in investigating the effect of the metal species of the metal fine wire used to connect the electrodes. The initial arc voltage was evaluated while varying the electrode gap. A comparison of the three metals Cu, Ni, and Pt revealed no significant difference, suggesting that the arc voltage does not depend on the fine wire material but rather on the electrode rod material and the electrode gap.

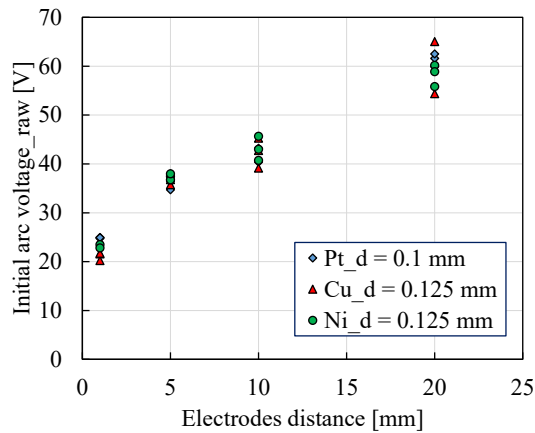


Figure 0-7 Influence of different metal species on the initial arc voltage

3.3.2 Effects of the discharge atmosphere (gas species and pressure)

The experimental results described in the previous subsection were obtained in air. Because self-decomposition reaction evaluation tests are conducted in high-temperature, high-pressure refrigerant atmospheres, it is also necessary to investigate the effects of the gas species and pressure. The tests were conducted under an electrode gap of 1 mm and a current limiter of 100 A. As the gas species, R32, which has no double bond and therefore no risk of self-decomposition reaction propagation, was selected for testing in a refrigerant atmosphere. However, because its saturated vapor pressure at room temperature is 1.47 MPa, heating is required to conduct tests at high pressure. Therefore, as an alternative, tests were conducted in an N_2 atmosphere, in which pressure can readily be adjusted, and the effect of pressure was investigated, as shown in Figure 3.3-8. The test results in N_2 indicated that the initial arc voltage tends to increase with increasing pressure. Typical discharge characteristics obtained in the R32 and N_2 atmospheres are shown in Figure 3.3-9. In the N_2 atmosphere, the arc voltage increased sharply soon after discharge began, and the arc was extinguished during the application period. These phenomena are considered to contribute to increased uncertainty in discharge energy. The

increase in arc voltage indicates an increase in arc length; once the arc reaches a certain length, it is extinguished and the circuit becomes open, causing the voltage to rise to the applied voltage of 200 V. By contrast, although the arc voltage tended to rise more than in air, it was relatively more stable than in N₂, and the discharge was more likely to continue for the intended application time. These results show that the arc is more stable in an R32 atmosphere than in N₂, which is the same conclusion as that obtained when the contact separation electrodes described in Section 3.2 were improved. Because the specific heats of N₂ and R32 differ, the rate of temperature rise of the surrounding gas during arc generation also differs. We consider that when the gas expansion ratio due to temperature change is small, as in the case of R32, changes in arc length are also small, and consequently, the arc voltage becomes more stable.

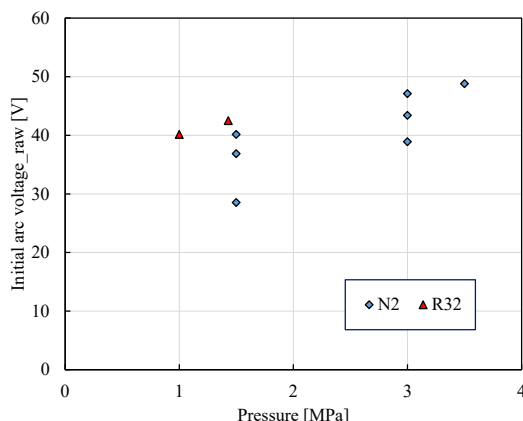
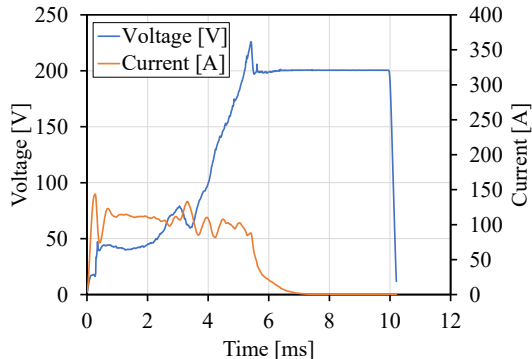
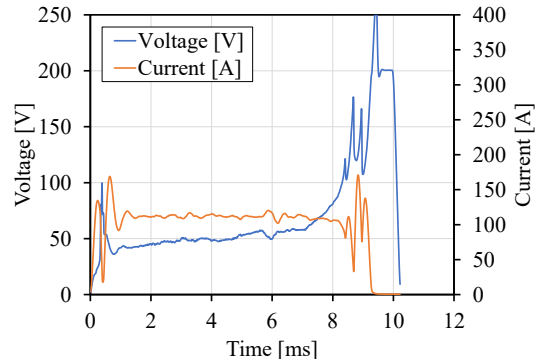


Figure 0-8 Influence of the type of environmental gas and pressure on the initial arc voltage



(a) Discharge in 1.5 MPa N₂.



(b) Discharge in 1.4 MPa R32.

Figure 0-9 Comparison of arc discharge in N₂ and R32 environments

3.4 Validation of the fusing wire and discharge method

3.4.1 Interlaboratory comparison test for confirmation of consistency

To internationally standardize a self-decomposition reaction evaluation method using the fusing wire and discharge method as the ignition method, it is necessary to confirm the consistency required by international standards, i.e., that the same results are obtained even when tests are conducted by different organizations. For this reason, an interlaboratory comparison test using R1132a as the standard substance was conducted by three institutions within Safety Gr. Because the reaction boundary pressures obtained by each institution under the conditions of 150 °C, an electrode gap of 1 mm,

and a discharge energy of 25 ± 5 J were within the allowable error range, the consistency of the evaluation method was confirmed. This section describes the results obtained by AGC.

The test was conducted under conditions of a current limiter of 150 A and application of DC 200 V for approximately 5 ms by the regulated power supply. The test results are shown in Figure 3.4-1. These results indicate that, when the discharge energy is 25 ± 5 J, the boundary pressure at which the self-decomposition reaction propagates is approximately 1.28 MPa. This value is substantially lower than the boundary pressure of 3.0 MPa reported in a previous study (Lisochkin *et al.*, 2006), which was obtained at 100 °C using the fusing wire method with an input energy of 19 J. This suggests that differences in the ignition method and the electrode structure used contribute to the difference in boundary pressure.

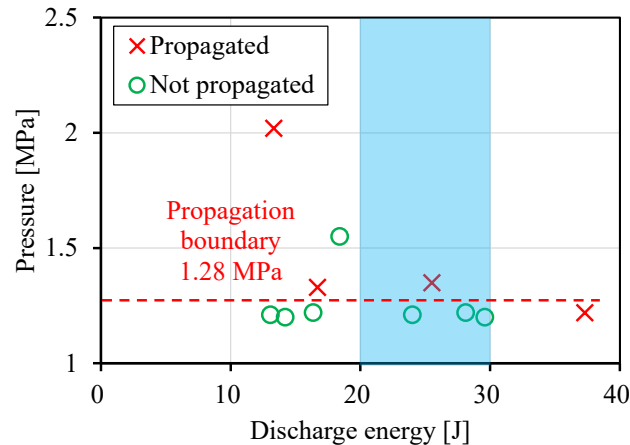


Figure 0-1 Pressure boundary for R1132a obtained using the fusing wire and discharge method with a discharge energy of 25 ± 5 J

3.4.2 Comparative evaluation with different ignition methods

Because the test results obtained in the previous subsection for confirming the consistency of the evaluation method were much lower than the literature values obtained using the fusing wire method, it is necessary to clarify the reason for this before international standardization can be achieved. In this section, tests were performed using the following six different ignition methods with different electrode structures, and the effects of the electrode structure and the physical phenomena reproduced were investigated by comparing the boundary pressures for the propagation of the self-decomposition reaction of R1132a at 150 °C.

- Fusing wire and discharge method using the Ni wire.
- Fusing wire and discharge method using the Cu wire.
- Direct-current discharge method using copper spiral electrodes (ignition method used in the preceding NEDO project).
- Alternating-current discharge method using contact separation electrodes (AGC's previous ignition method).
- Direct-current discharge method using contact separation electrodes (AGC's improved ignition method).
- Platinum-wire fusing method.

Figure 3.4-2 shows the four types of electrode structures used in the above ignition methods. The detailed test results obtained by each ignition method are shown in Figure 3.4-3. From the results for the various ignition methods, it was found that the boundary pressure can be grouped according to the electrode structure. The boundary pressures for propagation of the self-decomposition reaction obtained by the ignition methods using the electrodes for the fusing wire and discharge method were 1.25 and 1.28 MPa, indicating that the effect of the difference between the Cu and Ni wire is small. In the direct-current and alternating-current discharge methods using AGC's contact separation electrodes, the

energy densities should differ, yet the boundary pressures were found to be 2.74 MPa and 2.5–3.0 MPa, respectively. This result suggests that factors other than the difference in energy density exert a greater influence. In the direct-current discharge method using the spiral electrodes employed in the preceding NEDO project, the boundary pressure was 1.79 MPa, which lies between the values obtained with the preceding two types of electrodes. In addition, for the platinum-wire fusing method, which is commonly used owing to its simplicity, the boundary pressure obtained using a $\phi 0.5$ mm Pt wire was 2.86 MPa.

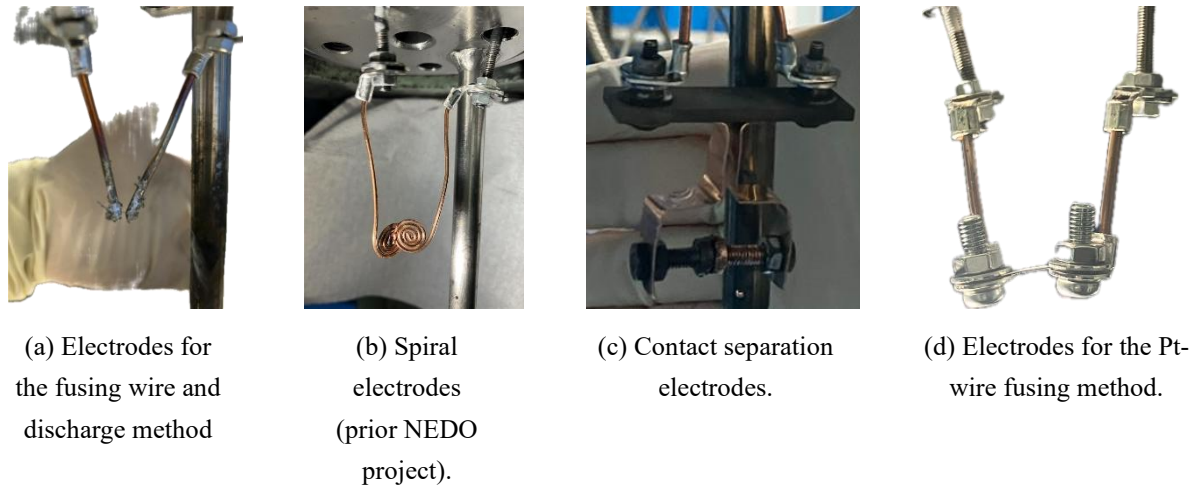
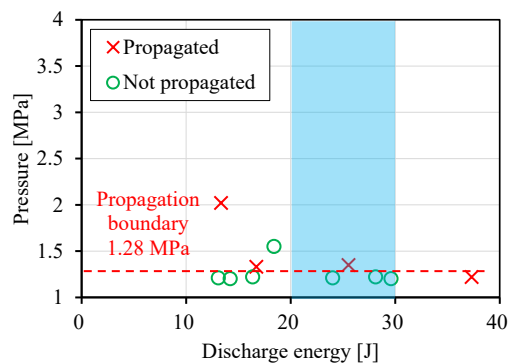
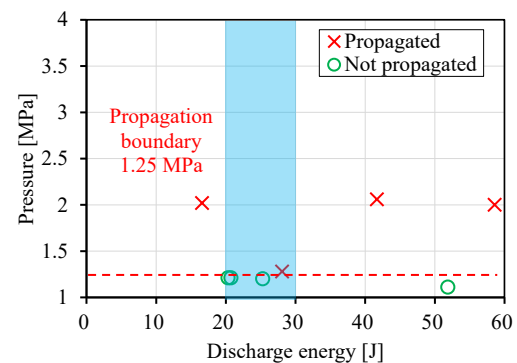


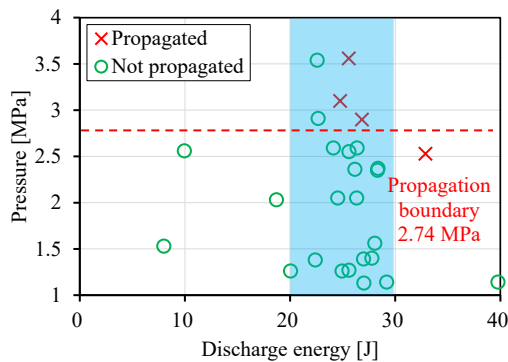
Figure 0-2 Electrode structures used in this study



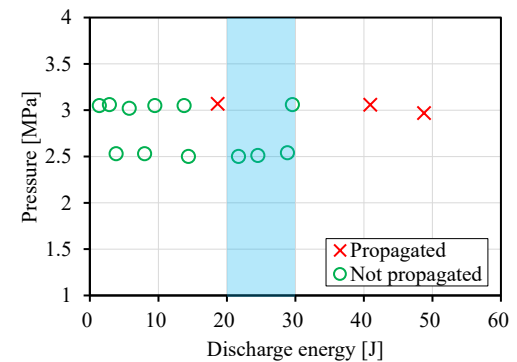
(a) Fusing wire and discharge method using the Ni wire.



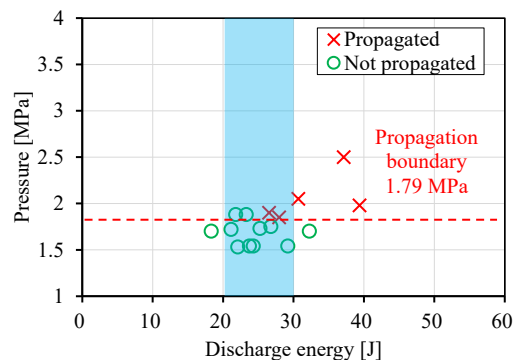
(b) Fusing wire and discharge method using the Cu wire.



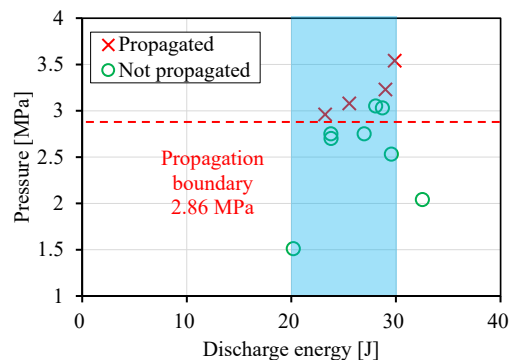
(c) DC discharge method with contact separation electrodes.



(d) AC discharge method with contact separation electrodes (at 100 °C).



(e) DC discharge method with spiral electrodes.



(f) Pt-wire fusing method.

Figure 0-3 Propagation boundaries for ignition methods using different electrode structures

The boundary pressures obtained with the different electrode structures decreased in the following order: electrodes used in the platinum-wire fusing method > AGC's contact separation electrodes > spiral electrodes > electrodes used in the fusing wire and discharge method. This order was consistent with the relative ease with which heat generated by discharge or fusing dissipated in the four electrode structures. For example, in the platinum-wire fusing method, the wire is approximately five times thicker than that used in the fusing wire and discharge method, and the time required for fuse breakage differs substantially. Under these conditions, heat loss conducted through the platinum wire becomes significant. These observations suggest that, as the amount of metal surrounding the discharge or fusing site increases, a larger fraction of the generated heat is lost through heat transfer at the metal surface, thereby substantially reducing the amount of heat actually transferred to the surrounding gas. Accordingly, the dependence of the self-decomposition reaction boundary pressure on the ignition method can be attributed to differences in the fraction of the total input energy transferred from the ignition point to the surrounding gas, even when the total input energy is nominally the same. This finding is also important for risk assessment. Among the ignition methods examined, the fusing wire and discharge method currently being considered for international standardization transfers energy to the surrounding gas most effectively and may therefore overestimate the propagation risk of self-decomposition reactions in actual equipment. These results suggest that appropriate risk assessment requires a consideration of the thermal environment surrounding the discharge site within actual refrigerant compressors.

3.4.3 Effect of test temperature on the propagation boundary conditions of self-decomposition reactions

In the evaluation method for self-decomposition reactions, the maximum temperature is assumed to be the thermal demagnetization temperature of the magnet inside the refrigerant compressor (150 °C). However, evaluation at room temperature may be used as a substitute to efficiently obtain the data required for risk assessment. Therefore, in this study, the temperature dependence of the boundary pressure for propagation of the self-decomposition reaction obtained using the fusing wire and discharge method was investigated. The results at 65, 100, and 150 °C are shown in Figure 3.4-4. From the test results, although tests were conducted under these three temperature conditions, no significant difference in boundary pressure was observed, and the boundary pressure was found to be approximately 1.3 MPa. At higher temperatures, the frequency of molecular collisions increases, which tends to enhance reactivity. Conversely, because the tests were conducted at the same pressure, the molecular density becomes lower at higher temperatures, which decreases the collision frequency and thus tends to reduce reactivity. We concluded that the reason for the similar boundary pressures was because these two effects offset each other.

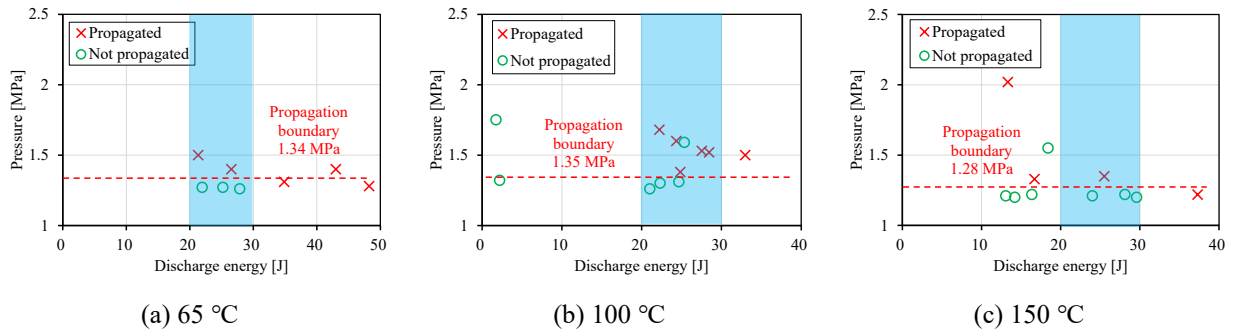


Figure 0-4 Temperature dependency of the propagation boundary for the fusing wire and discharge method

3.5 Development of HFO-1123 refrigerant mixtures

In response to the demand for a transition to low-GWP refrigerants, the maximum blending ratio of HFO-1123 was investigated assuming a ternary refrigerant mixture system of HFO-1123/R32/R1234yf to develop a refrigerant mixture with a GWP of 150 containing HFO-1123. Because the GWP was fixed at 150, the blending ratio of R32 was fixed at 21.5 mass%. The ignition method used was the direct-current discharge method with contact separation electrodes under a current-limiter condition of 378 A. The tests were conducted under conditions of 130 °C and 4 MPa, assuming the normal operating conditions of residential air conditioners. The test results are shown in Figure 3.5-1. For the composition containing 45 mass% HFO-1123, no propagation of the self-decomposition reaction was observed even when 30 J of energy was supplied. For the composition containing 50 mass% HFO-1123, the reaction did not propagate when the discharge energy was 30 J, but propagation of the self-decomposition reaction occurred at 34.4 J. This result suggests that, for a composition containing 50 mass% HFO-1123, the threshold ignition energy for the propagation of the self-decomposition reaction lies near 30 J. For the composition containing 60 mass% HFO-1123, the threshold ignition energy was found to be below 20 J. Therefore, under conditions assuming normal operation, if energy up to 30 J is supplied, compositions with an HFO-1123 blending ratio of up to 50 mass% do not allow the propagation of self-decomposition reactions. This result is meaningful for composition development to improve the cycle performance of refrigerant mixtures containing HFO-1123.

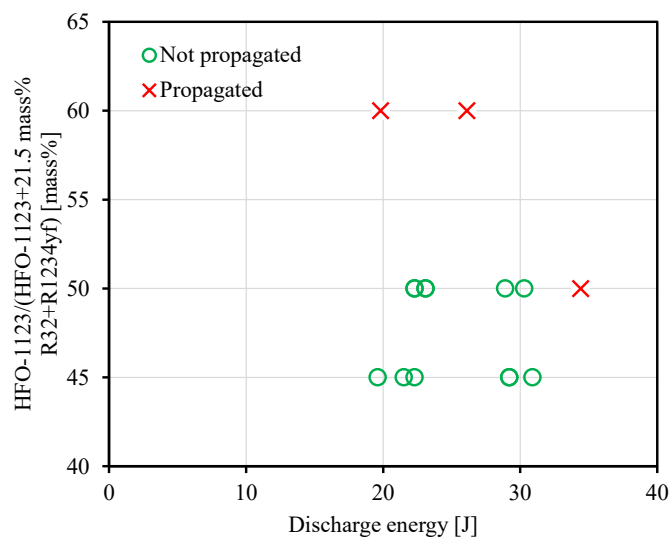


Figure 0-1 Experimental results varying the HFO-1123 concentration and discharge energy

3.6 Summary

In this study, efforts were made toward the international standardization of a method for evaluating self-decomposition reactions, which are indispensable for the dissemination of HFO refrigerants. These efforts included improvements to the AGC's ignition method, verification of interlaboratory reproducibility using the fusing wire and discharge method proposed by Safety Gr. as the ignition method to be used in the international standard, and the acquisition of fundamental test data providing the basis for its validity as a discharge ignition method. Appropriate risk assessment was ensured by comparing the proposed ignition method with others. The findings clarified that the boundary pressure depends on the electrode structure. In addition, the maximum blending ratio of HFO-1123, which is a candidate next-generation refrigerant, under specified conditions was also investigated to improve the cycle performance of refrigerant mixtures containing the refrigerant.

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4. Development of Self-Decomposition Reaction Evaluation Methods and Safety Verification of Refrigerant Mixtures Containing R1132(E) (Daikin Industries)

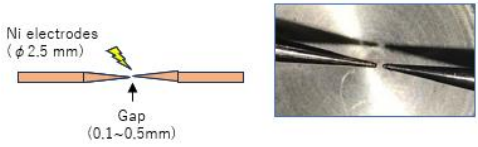
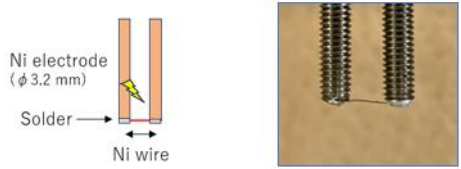
4.1 Development of self-decomposition reaction evaluation methods

A discharge test apparatus capable of operating under high gas pressures was developed to establish a test method suitable for evaluating self-decomposition reactions in air-conditioning equipment, and studies directed toward standardization were conducted. Using this test method, the limiting R1132(E) concentration for the propagation of self-decomposition reactions in mixtures with R1234yf and related refrigerants was examined. In addition, the mechanism of self-decomposition reactions was investigated, and the risks anticipated during use in air conditioning equipment were assessed to provide information relevant to determining the need for equipment-level countermeasures. This section first describes the development of an apparatus capable of generating discharge under high-pressure conditions.

4.1.1 Overview of the evaluation apparatus

In the conventional self-decomposition reaction evaluation apparatus, the dielectric breakdown method was adopted. In this method, no contact point exists between the electrodes, and a momentary high voltage (40 kV) is applied across the electrodes to accelerate electrons and generate an arc. By contrast, in the newly developed fusing wire and discharge method, a contact point is created by bridging the electrodes with a fine metal wire, and the temperature at the contact point is raised by energization. Subsequently, melting and evaporation of the fine metal wire occur, and thermionic or field emission renders the space between the electrodes electron-rich, thereby enabling discharge even at low voltage. Table 4.1-1 summarizes the electrode structures and principal specifications of each apparatus.

Table 0-1 Characteristics of discharge devices

Contents	Dielectric breakdown method (conventional equipment)	Fusing wire and discharge method (new device)
Electrode structure		
Discharge mechanism	· Accelerate the electrons between the electrodes by applying a high voltage. · Cause dielectric breakdown and ionize the refrigerant molecules. · Current flows through the electron-rich region between the electrodes, producing a discharge.	· Apply a voltage across the electrodes to melt and break the thin metal wire. · Thermionic electrons are emitted from the molten metal during fuse breakage. · Current flows through the electron-rich region between the electrodes, producing a discharge.
Input voltage	DC: ~ 2000 V (capacitor)	DC: ~ 230 V
Discharge energy	~ 250 J	~ 100 J
Testable pressure level	~ 3 MPa	~ 6 MPa
Features	· High reproducibility of discharge energy. · Use fixed electrodes. · A power supply capable of generating high voltage is required.	· High reproducibility of discharge energy. · Use fixed electrodes. · Lower device cost and easier electrode adjustment.

An easily obtainable regulated power supply can be used as the power source for the fusing wire and discharge method, allowing control of the current and, as such, the adjustment of the discharge power. In addition, the discharge energy can be adjusted by controlling the discharge duration with a cut-off switch. Figure 4.1-1 shows the waveform at the time of discharge generation. From the discharge waveform, we confirmed that metal melting occurs initially and, after breakage, the process transitions to arc discharge.

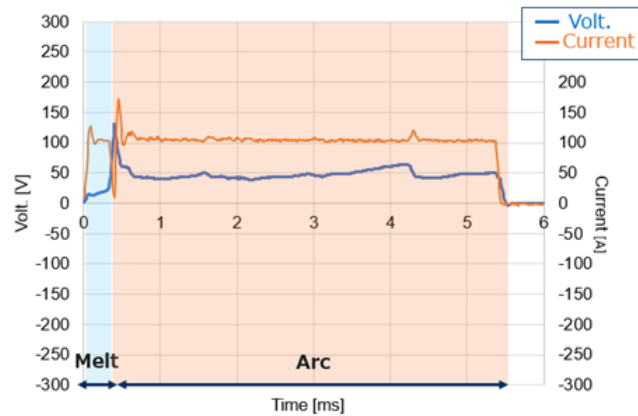


Figure 0-1 Discharge waveform of the fusing wire and discharge method

4.1.2 Parameters affecting discharge behavior

For the evaluation of refrigerant self-decomposition reactions, the test apparatus is required to generate and sustain discharge stably even under high gas-pressure atmospheres. Therefore, the correlation between the items listed in Table 4.1-1 and the maximum discharge distance was examined to identify apparatus parameters that affect the discharge phenomenon. A longer maximum discharge distance indicates a structure in which discharge is more easily sustained. Opposed electrodes were used, and a fine metal wire was bridged between them and fixed with nuts.

Table 0-2 Device parameters

No.	Contents		Observation points
①	Metal wire	Material	Differences in melting point, boiling point, and work function
		Wire diameter	Changes in behavior up to fuse melting / breakage
②	Gas temperature and pressure		Cooling of the arc column (ionization state)
③	Voltage		Maintenance of thermionic electron emission in the arc column (ionization state)
④	Electrode gap		Cooling of the arc column

(1) Fine wire

Figure 4.1-2 presents plots of the maximum discharge distance from three viewpoints: melting point, boiling point, and work function. Cu electrodes were used, and verification was performed under air and R32 atmospheres. The voltage was fixed at 60 V. Under air, the maximum possible discharge tended to increase as the melting point and boiling point of the fine wire increased. By using a fine wire with a high melting point, the local temperature around the electrode at the time

of arc generation becomes higher, which may have (1) promoted thermionic emission from the electrode and (2) suppressed the cooling effect on the arc column. Conversely, the absence of dependence on the work function of the fine wire indicates that the influence of thermionic emission from the fine wire is small. No clear trend was observed under the R32 atmosphere because soot and related products generated during the R32 decomposition adhered to the electrodes and interfered with arc formation. Other evaluations, including wire diameter, also showed no difference in maximum discharge distance. From these results, the type of fine wire is considered to have a minor effect on the self-decomposition reaction evaluation.

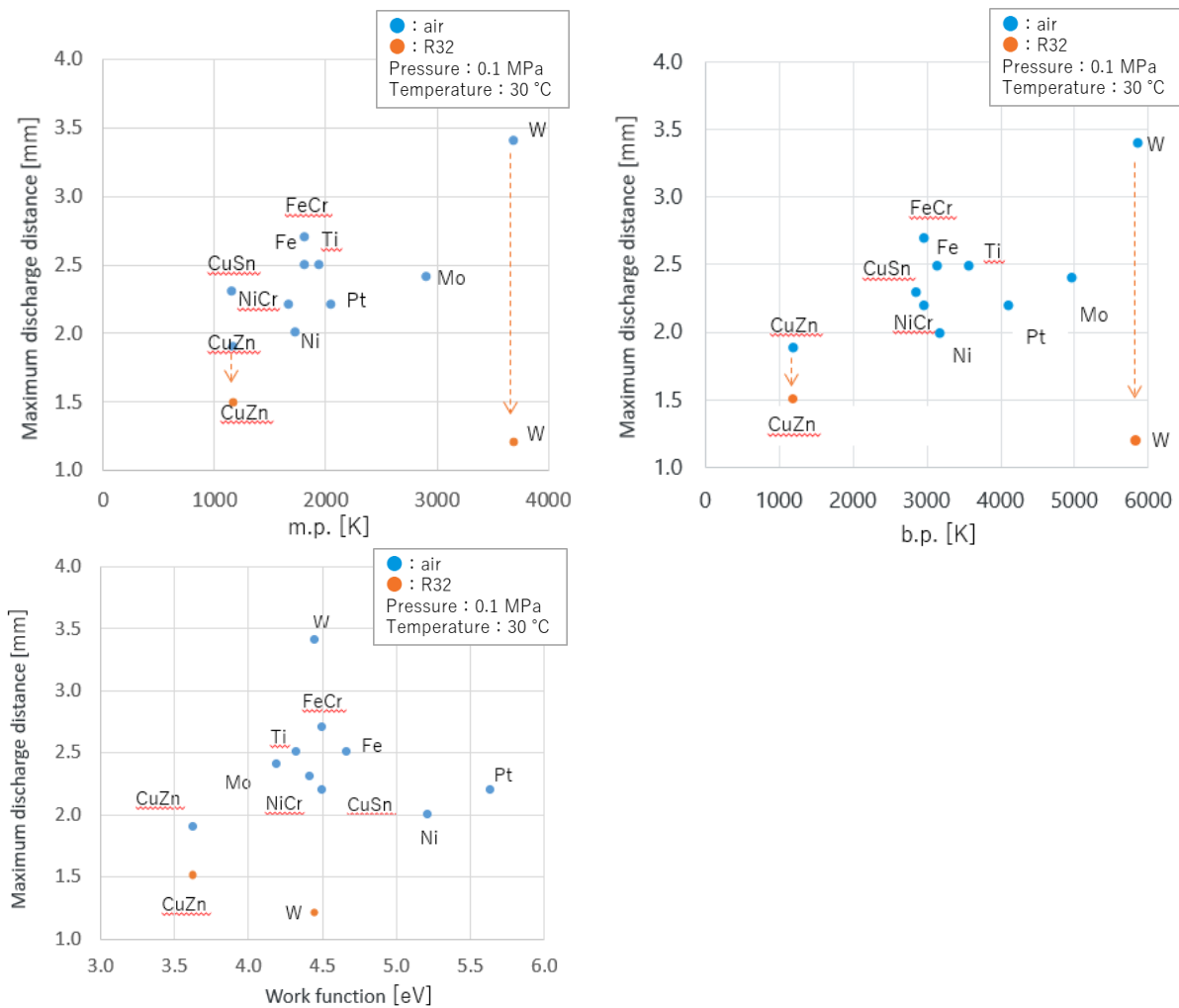


Figure 0-2 Relationship between the melting point / boiling point / work function and maximum discharge distance

(2) Pressure and temperature

The effects of gas pressure (density) and temperature on the maximum discharge distance were evaluated. The results for pressure are shown in Figure 4.1-3, and the results for temperature are shown in Figure 4.1-4. The voltage was fixed at 60 V.

In terms of gas pressure (density), the evaluation was performed using four wire metals, and in all cases a clear correlation was observed: as the pressure (density) increased, the maximum discharge distance became shorter. Possible reasons for this pronounced correlation include (1) the mean free path of ionized electrons in the arc region becoming shorter as gas density increases, making it difficult to maintain the ionized state, and (2) the arc column being cooled and its temperature reduced, which also makes it difficult to maintain the ionized state.

With respect to temperature, when either the W or CuZn fine wire was used, no difference in discharge distance was observed over the 30–150 °C range. In contrast to the ionization temperature of the arc column, which reaches several thousand Kelvin, the temperature range assumed in self-decomposition evaluation is only on the order of 100 K, and this is considered the reason no effect was observed. These results indicate that, under the high-pressure conditions relevant to self-decomposition evaluation, discharge generation is expected to become more difficult.

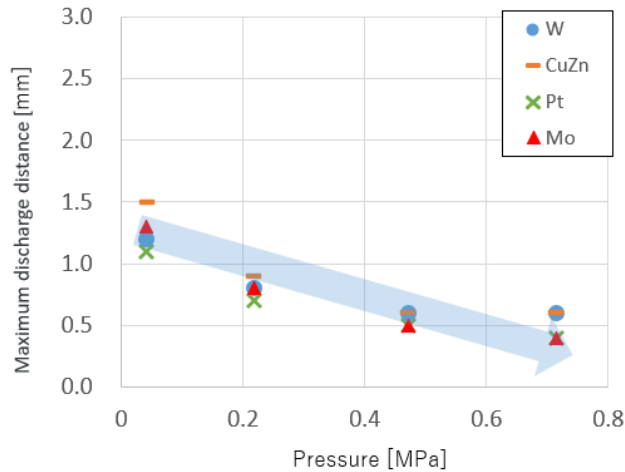


Figure 0-3 Correlation between pressure and the maximum discharge distance

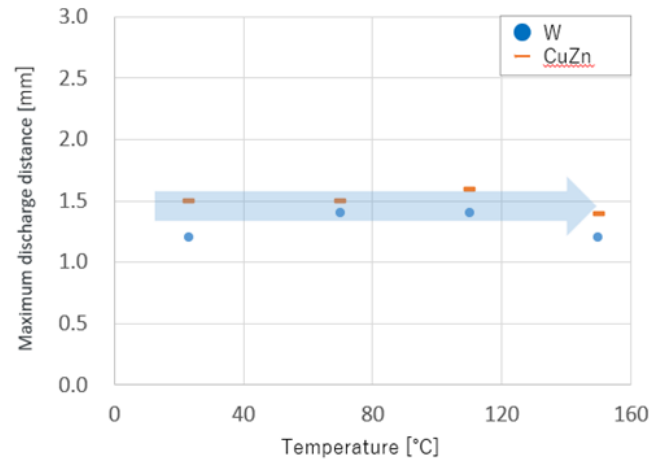


Figure 0-4 Correlation between temperature and the maximum discharge distance

(3) Voltage

Figure 4.1-5 shows the changes in the maximum discharge distance as a function of interelectrode voltage. Evaluation was performed in air and R32 at 30 °C and atmospheric pressure. In both cases, the maximum discharge distance tended to increase as the voltage increased. The ionized electrons accelerate more effectively with increasing voltage, thereby making it easier to maintain the ionized state.

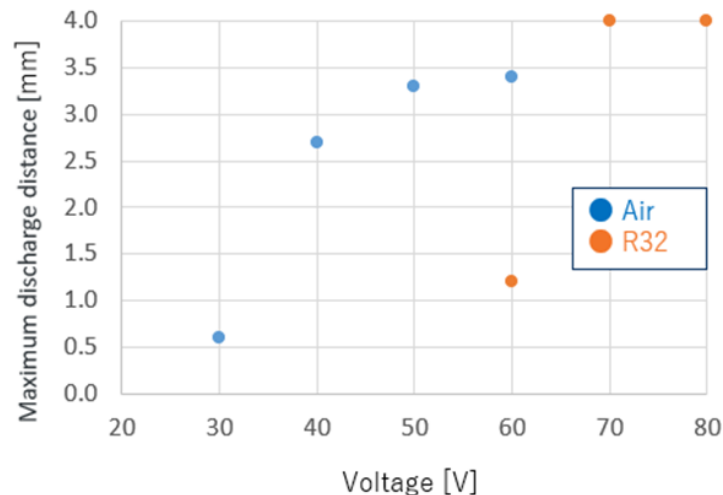


Figure 0-5 Correlation between voltage and the maximum discharge distance

From these test results, it was confirmed that the maximum discharge distance (i.e., the ease with which discharge occurs) depends strongly on pressure (density) and the power-supply voltage.

4.1.3 Evaluation conditions for self-decomposition reactions

The test conditions for self-decomposition reactions were established with reference to a method based on the stability test for flammable gases specified in TDG. The test conditions are shown in Table 4.1-3; for refrigerant mixtures, the worst-case formulation (WCF) composition was used. Based on these conditions, Figure 4.1-6 illustrates the overall configuration of the test apparatus fabricated by our company. The electrodes are fixed to the pressure vessel by insulators, and a fine metal wire is bridged across the electrode tips. With respect to the temperature and pressure conditions for refrigerant evaluation, the normal operating range of R32, a high-pressure refrigerant widely used in air conditioners, is approximately 65 °C and 4 MPa. However, high-temperature and high-pressure environments under abnormal conditions, such as equipment failure, must also be considered. Because the temperature and pressure corresponding to a specific failure mode cannot be uniquely specified, the maximum abnormal temperature was set to 150 °C, considering the demagnetization temperature of the permanent magnet used in the motor. The maximum abnormal pressure was set to 1.5 times the saturated pressure at 65 °C, based on the compressor design pressure. For refrigerants with a critical temperature of 65 °C or lower, the maximum abnormal pressure was set to 1.5 times the critical pressure. Self-decomposition was judged to have occurred when the pressure reached at least 1.3 times the initial pressure. As noted in Section 2.2, discussions on this test method as an evaluation method for the new stability classification in ISO 817 are currently ongoing.

Table 0-3 Test conditions

Parameter		Value
Electrodes	Gap	1.0±0.1 mm
	Wire material	Ni
	Wire diameter	Φ 0.12 mm
Vessel	Shape	Cylindrical
	Volume	>0.25 L
	Diameter	50±10 mm
Ignition	Source	AC/DC
	Time	max. 10 ms
	Energy	25±5 J (or 10±2 J)
Refrigerant	Composition	WCF
	Pressure	Saturated pressure ×(1.5±0.1) MPa
	Temperature	150 °C

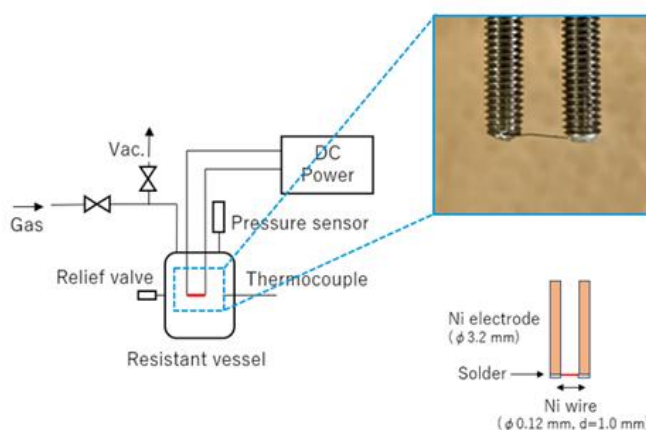


Figure 0-6 Device configuration

4.1.4 ILC test

Under the test conditions described in Section 4.1.3, an interlaboratory comparison was conducted using R1132a. The test results obtained at our company are shown in Figure 4.1-7. For R1132a, we confirmed that the self-decomposition reaction boundary exists at approximately 1.3–1.5 MPa. As described in Section 2.5, when the width between the UBP and LBP is considered in the ILC, the results from all institutions fall within ±5% of the average value, indicating that the method provides consistent results even among different testing institutions.

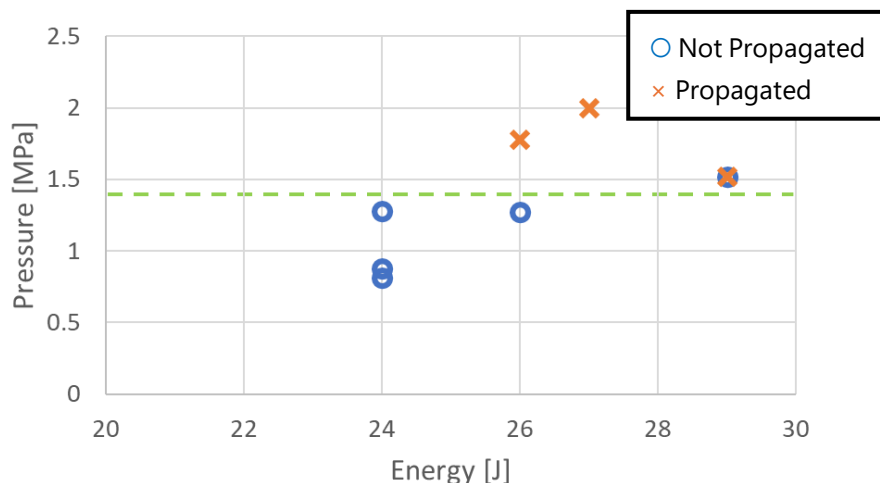


Figure 0-7 Evaluation of the boundary conditions for R1132a

4.1.5 Evaluation of vessel dependence

The influence of the test-vessel volume was evaluated to identify the parameters affecting the judgment results. Figure 4.1-8 shows the test results obtained under conditions equivalent to those of the ILC test using different vessel volumes (38 cc, 100 cc, and 500 cc). No differences were observed among the three tested conditions. From these results, with the height of the internal space of the vessel denoted by L and the inner diameter by D , it was clarified that, for vessels with an L/D ratio of 1.2, the vessel volume does not affect the boundary pressure for the occurrence of self-decomposition reaction propagation and that substantially the same result is obtained as long as the vessel volume is at least 38 cc (the minimum).

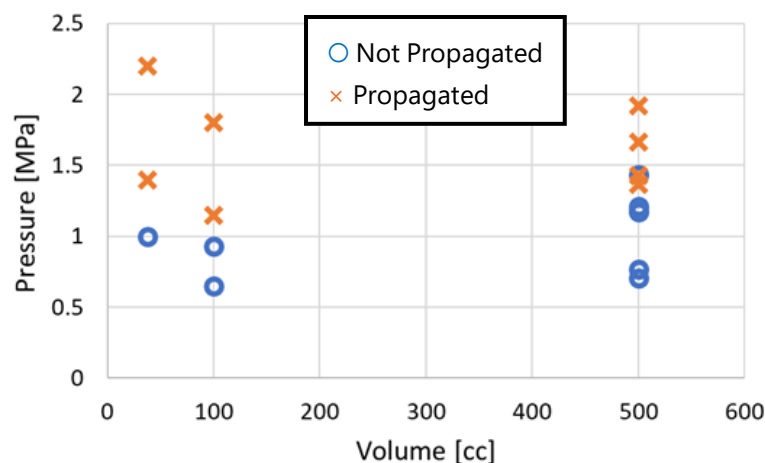


Figure 0-8 Evaluation of vessel-volume dependence for R1132a

4.2 Clarification of the boundaries of the self-decomposition reactions of R1132(E)/R1234yf refrigerant mixtures under various conditions

4.2.1 Boundaries of the self-decomposition reactions in R1132(E)/R1234yf refrigerant mixtures

Among the currently registered refrigerant mixtures containing R1132(E), self-decomposition evaluation was performed for R474B, which has the highest R1132(E) concentration, under the test conditions described in Section 4.1.3. The refrigerant composition used was the WCF composition of R474B, namely R1132(E)/R1234yf = 33.5/66.5 mass%.

The test conditions are shown in Table 4.2-1. When the test was conducted with $n = 3$, no self-decomposition reaction occurred in all cases. The temperature and pressure waveforms obtained in the test are shown in Figure 4.2-1. Concurrently with arc discharge generation, a pressure rise of approximately 0.1 MPa was observed. This pressure rise is considered to have been due to thermal decomposition of the refrigerant at the arc discharge region. However, no temperature rise was observed at all.

From these results, under the stability test method currently proposed for ISO 817, R474B falls into Class α (sufficiently stable for general use). In addition, R474A is also expected to fall into the same class because its R1132(E) concentration is low. In the future, R479A will be evaluated. Furthermore, based on the ILC test results and the evaluation of the dependence on apparatus parameters, the soundness of the evaluation method was confirmed. We will continue discussions on test methods within the ISO task force, re-evaluate the refrigerants using finalized methods, and determine their classification.

Table 0-1 Test conditions

Parameter		Value
Ignition	Source	DC 200 V
	Time	<5 ms
	Energy	Apx. 25 J
Refrigerant	Composition	R1132(E)/R1234yf =33.5/66.5 mass%
	Pressure	4.4 MPa · A
	Temperature	150 °C

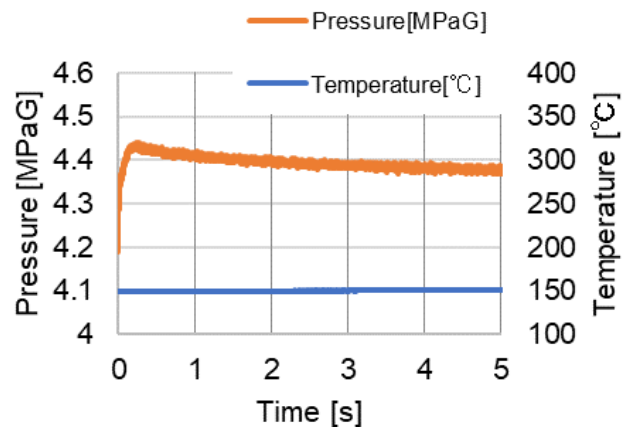


Figure 0-1 Pressure and temperature waveforms

4.2.2 Comparison with the dielectric breakdown method

The behavior of self-decomposition reactions in R1132(E)/R1234yf refrigerant mixtures was examined to clarify the effect of the test method. The test conditions were based on those described in Section 4.1.3, except that the pressure was varied and the input energy was set to 10 J, representing an energy level that may occur in actual equipment. As in the other evaluations, self-decomposition was judged to occur when the pressure reached at least 1.3 times the initial pressure. In Figure 4.2-2, results obtained using the dielectric breakdown method are shown in red, whereas those obtained using the fusing wire and discharge method are shown in blue. In this study, comparison tests were conducted at R1132(E)/R1234yf = 70/30 mass% to confirm consistency, and agreement between the two methods was verified. In future work, additional test points spanning a broader pressure range, including higher-pressure conditions, will be examined to further clarify the influence of discharge characteristics on self-decomposition reactions.

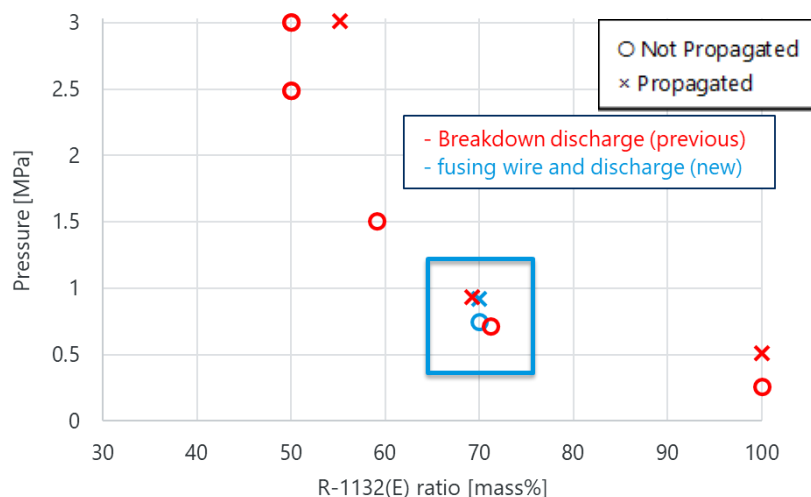


Figure 0-2 Comparison between the fusing wire and discharge and dielectric breakdown methods

4.3 Elucidation of the mechanism of self-decomposition reactions

We investigated the mechanism of self-decomposition reactions by adopting an approach in which multiple hypotheses were first formulated and then assessed to identify the one most consistent with the experimental results. For theoretical verification, the general-purpose quantum chemistry program, Gaussian 16W, was used, and the plausibility of the proposed pathways was examined by calculating the energy changes associated with structural transformations. The evaluation of the candidate hypotheses suggested that two pathways are plausible based on the calculated energy profiles: ① one in which two fluoro-olefin molecules associate and undergo structural rearrangement, and ② another in which a single fluoro-olefin molecule enters an excited state and then undergoes structural rearrangement (Figure 4.3-1). In future work, these hypotheses will be compared with experimental findings to identify the pathway most consistent with the observed results and further clarify the reaction mechanism.

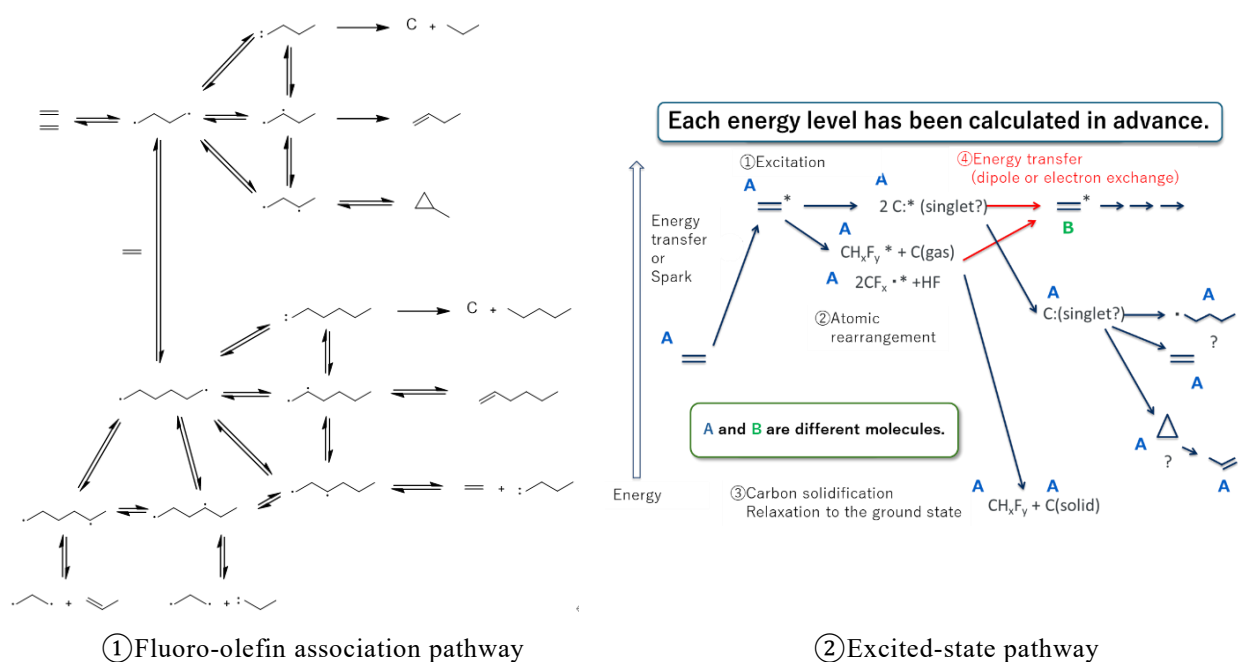


Figure 0-1 Possible pathways inferred from the energy diagram

4.4 Issues and responses regarding the practical implementation of safety measures for the dissemination of next-generation low-GWP refrigerants

The issues associated with dissemination were organized using the outcomes of this project, and solutions, including legal requirements, were examined to enable the practical implementation of safety measures against self-decomposition reactions and to globally disseminate next-generation low-GWP refrigerants.

The issues related to dissemination were defined as the “global dissemination of next-generation low-GWP refrigerants for which practical safety measures against self-decomposition reactions have been implemented.” They were classified into (1) creating an environment where equipment manufacturers worldwide adopt them as refrigerants, and (2) establishing their position globally as a viable option for compliance with the Kigali Amendment and global warming mitigation. Item (1) was further classified into an examination of a mechanism that ensures that equipment patents held by multiple companies do not hinder the adoption of next-generation low-GWP refrigerants and an examination of a mechanism that prevents the inability to use next-generation low-GWP refrigerants effectively owing to a lack of know-how. Item (2) was addressed as an examination of a mechanism for effective public promotion.

4.4.1 Examination of a mechanism to prevent equipment patents held by multiple companies from becoming obstacles to the adoption of next-generation low-GWP refrigerants

As a mechanism for ensuring that equipment patents related to air conditioners and refrigeration equipment using next-generation low-GWP refrigerants (hereinafter, equipment patents) do not hinder adoption, consideration was given to a framework for the reciprocal use of equipment patents that would facilitate their implementation. This examination was advanced via consultation with experts in intellectual property and antitrust law, together with interviews with equipment manufacturers (19 times).

Under the framework for reciprocal use of equipment patents that facilitates their implementation (hereinafter, the new mechanism), an organization for managing and operating the new mechanism (hereinafter, the organization) would be

established, and the organization would identify a set of eligible patents using objective and rational search criteria that exclude arbitrariness. The identified set would comprise patents related to the technologies required when adopting HFO-1123 or HFO-1132 as refrigerants in air conditioners and refrigeration equipment[※]. Equipment-patent holders would be able to choose whether to participate in the new mechanism.

Patent royalties for the equipment patents covered by the new mechanism would be set to a fixed fee per unit weight of the target refrigerant, thereby keeping royalties low in view of broad dissemination. The royalties would be collected through sales of the target refrigerant and managed by the organization.

Based on the above examination, the initiative will move toward the establishment of an operating organization for the new mechanism that will prevent violations of antitrust law in advance and fully realize the expected competition-promoting effects.

※) As of March 23, 2026, the refrigerant mixtures registered with ASHRAE and assumed for use when adopting HFO-1123 or HFO-1132 as refrigerants in air conditioners and refrigeration equipment are R474A, R474B, R479A, R479B, and R491A.

4.4.2 Examination of a mechanism to prevent the inability to utilize next-generation low-GWP refrigerants owing to a lack of know-how

Know-how can be classified into “know-how related to the design, manufacture, and other aspects of equipment using next-generation low-GWP refrigerants” and “know-how related to the installation, maintenance, disposal, and other handling of next-generation low-GWP refrigerants.” Such know-how may contribute to safety, efficiency, and economic performance through energy conservation.

With respect to this topic, the following general issues were identified: (1) know-how related to equipment design and manufacturing often includes plant- or company-specific elements that cannot be used directly by other companies and is highly confidential for each company. (2) Equipment manufacturers generally lack the know-how related to installation, maintenance, disposal, and related work. Instead, it is acquired experientially by on-site technicians and tradespeople at installation contractors or refrigerant charging/recovery companies, and in most cases is not patented. However, it was concluded that companies have already accumulated considerable experience through the widespread use of R32 as an A2L refrigerant and that no new formal mechanism is required to manage this know-how.

4.4.3 Examination of a mechanism for effective public promotion

For the global dissemination of next-generation low-GWP refrigerants, for which practical safety measures against self-decomposition reactions have been implemented, it is particularly important to establish them in countries worldwide as an option for compliance with the Kigali Amendment and for climate change mitigation. Achieving this objective requires measures beyond the scope of private-sector activities alone, including engagement within the Montreal Protocol framework and responses to policy regimes such as the European F-gas Regulation and the REACH Regulation. Accordingly, coordinated action between the public and private sectors is essential, with each fulfilling its respective role.

Such cooperative public-private efforts may be advanced with each government, industry association, equipment manufacturer, and refrigerant manufacturer fulfilling its role; however, this is an initiative that requires sustained coordination, including confirmation of the fundamental perspectives and directions as well as the sharing of information obtained owing to the activities.

Through the program entitled “Comprehensive Development Including Human Resource Development and Industry-Academia Collaboration Centered on NEDO Projects / Special Course Related to the Development of High-Efficiency Refrigeration and Air-Conditioning Technologies for the Practical Implementation of Next-Generation Low-GWP Refrigerants,” NEDO aims to “conduct this project and surveys of related domestic and international technologies concerning technologies that lead research, development, and implementation of low-GWP refrigerants and equipment,

and to promote their early social implementation through public outreach, human resource development, and personnel exchange,” as well as to “develop an intellectual foundation for strengthening collaboration with related domestic and international industries and academia with a view toward international standardization such as ISO and ASHRAE.” Therefore, in relation to the mechanism whose establishment is being advanced in Section 4.4.1, coordination with this program may constitute an additional issue for consideration.

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5. Identification of Factors Inducing Self-Decomposition Reactions in Compressors and Development of an Energy Evaluation Method

(Suwa University of Science)

5.1 Introduction

Efforts to reduce the use of hydrofluorocarbons (HFCs) are ongoing to mitigate greenhouse gas emissions. Refrigerants constitute the largest application of HFCs, accounting for approximately 90% of total HFC emissions (Ministry of the Environment, 2023). Therefore, reducing the global warming potential (GWP) of refrigerants contributes substantially to lowering HFC-derived greenhouse gas emissions. Until the 2000s, R410A (GWP = 2,090 (Ministry of the Environment, 2026)) was widely used as the principal refrigerant owing to its favorable refrigerant performance and safety characteristics. Subsequently, R32 (GWP: 675), which has a relatively low GWP among HFC-based refrigerants, was adopted as an alternative refrigerant after the risk assessment of its mild flammability and the establishment of corresponding safety measures; it is now the principal refrigerant used in residential air-conditioning equipment. However, almost concurrently with the wider deployment of R32, new reduction targets were established under the Kigali Amendment to the Montreal Protocol, adopted in 2016 (Ministry of the Environment, 2017). Meeting these targets with R32 alone is expected to be difficult, necessitating the development and exploration of new alternative refrigerants. Certain HFO-based refrigerants, such as R1132(E), have GWPs of 1 or less and exhibit refrigerant performance equal to or greater than that of conventional refrigerants; therefore, they are promising alternative refrigerant candidates. Conversely, these refrigerants are known to undergo self-decomposition reactions when sufficient energy is supplied under specific conditions, such as high temperature and high pressure, raising concerns regarding severe human and material damage. Unlike combustion phenomena, self-decomposition reactions can occur even in the absence of an oxidizer. Thus, particularly inside compressors, where refrigerants are exposed to high temperatures and high pressures, the risk of self-decomposition reactions cannot be neglected. Therefore, preventing such reactions in advance is a critical requirement for the practical application of these refrigerants.

Against this background, factors that induce self-decomposition reactions inside compressors were investigated under the NEDO project “Development of Next-Generation Refrigerant and Refrigeration/Air-Conditioning Technologies and Evaluation Methods to Achieve Energy Conservation and Low Greenhouse Effects,” which was conducted through FY2022. In particular, “arc discharge generated during turn-to-turn short circuits between motor windings or ground faults” was identified as the most likely trigger of self-decomposition reactions. In that project, a research group at Shizuoka University investigated the energy generated during turn-to-turn short circuits, protective circuits, and compressor operating behavior (NEDO, 2023). However, discharge energy under refrigerant-atmosphere conditions has not yet been determined, and no method has been established to quantitatively evaluate the arc discharge energy generated in compressors under various operating conditions. In addition to arc discharge, frictional heat in the rotor sliding parts in compressors and tracking at electrical terminals have also been suggested as possible factors inducing self-decomposition reactions; however, these factors have not yet been quantitatively evaluated.

Therefore, this study aims to clarify the mechanisms by which factors inducing self-decomposition reactions inside compressors—including arc discharge energy and other potential sources—are generated through data collection and organization based on survey-based, theoretical, computational, and experimental approaches. Based on these findings, this study aims to develop an estimation model that quantitatively evaluates self-decomposition-inducing factors, including discharge energy, from compressor operating conditions and related parameters. The validity of the developed estimation model will be assessed through verification tests using a full-scale compressor model. In particular, phase-to-

phase short circuits and ground-fault phenomena between windings inside the compressor of a residential air conditioner were experimentally reproduced, and current and voltage waveforms and the visual behavior and spectra of the discharge plasma were obtained to determine discharge energy and to examine the effects of ambient conditions such as pressure. In addition, a computational method based on numerical simulations was developed to enable energy prediction without relying solely on experiments, and simplified theoretical equations were derived and evaluated. This report comprehensively describes the experimental and simulation results for phase-to-phase short circuits between windings in inverter-driven and constant-speed compressors.

5.2 Research methodology

5.2.1 Short-circuit experimental apparatus and method

The specifications of the inverter-driven compressors (hereinafter referred to as inverter compressors) and the constant-speed compressor used in this study are summarized in Table 5.2-1. The inverter compressors were taken from commercially available residential air conditioning equipment. Although residential air conditioning equipment equipped with constant-speed compressors has been used overseas, such equipment is rarely distributed in Japan; therefore, a constant-speed compressor installed in an actual refrigerator was used as a substitute. Equivalent circuit diagrams for the inverter and constant-speed compressors are shown in Figures 5.2-1 and 5.2-2, respectively. Part of the wiring connecting the power supply and compressor was branched and connected to the short circuit. Figure 5.2-3 shows a photograph of the short-circuit device. The device comprises a cylindrical SUS316 vessel with a volume of 1.5 L and a pressure resistance of 6.0 MPa, in which a pair of metal rods is installed facing each other at the center of the vessel. One metal rod (SUS316, diameter: 6.2 mm) is fixed to the vessel through an insulating joint, whereas the other rod (copper, diameter: 6.2 mm) is connected to the shaft of a stepping motor (Oriental Motor, ARM46AC-H50) and can move horizontally over a stroke of 10 mm. The branched wiring was connected to this pair of metal rods, and the movable electrode was advanced until the electrode surfaces came into contact, thereby producing a short circuit. The electrode surfaces were flat. The vessel was covered with a jacket heater, enabling a temperature increase within and outside the vessel to 150 °C. A pair of observation windows (diameter: 25 mm) was attached to the vessel to record the discharge behavior inside it. The internal pressure was monitored using a pressure transducer (Nagano Keiki, KH-15).

Table 0-1 Specifications of the test compressors of room air conditioners

(a) Single-phase AC200 V inverter-driven compressor (b) Single-phase AC100 V inverter-driven compressor

Power	Single-Phase AC200V
Refrigerant	R32
Rated performance	Cooling: 3.6 kW, Heatig: 4.0 kW
Consumption power	Cooling: 0.81 kW, Heating: 0.96 kW
Working current	Cooling: 4.45 A, Heating: 5.27 A
Power of compressor	0.56 kW

Power	Single-Phase AC100V
Refrigerant	R32
Rated performance	Cooling: 2.8 kW, Heatig: 3.6 kW
Consumption power	Cooling: 0.51 kW, Heating: 0.66 kW
Working current	Cooling: 5.50 A, Heating: 7.00 A
Power of compressor	1.10 kW

(c) Single-phase AC100 V constant-speed compressor

Power	Single-Phase AC100V
Refrigerant	R448A
Temperature	Evaporation: -10°C/Outside 32°C
Consumption power	1.02 kW
Working current	10.7 A
Power of compressor	0.60 kW

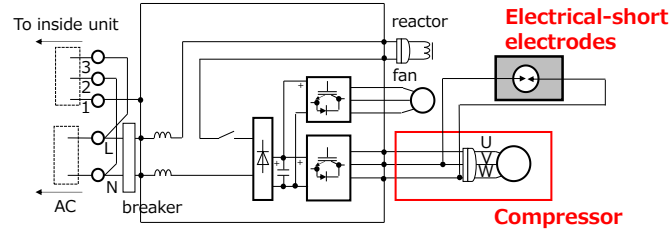


Figure 0-1 Schematic of the equivalent circuit of an inverter-driven room air conditioner

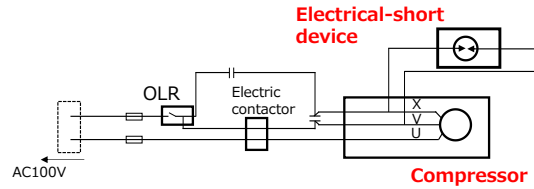


Figure 0-2 Schematic of the equivalent circuit of a constant-speed compressor-driven refrigerator



Figure 0-3 Overall view of the electrical-short device and enlarged view of the electrodes

The measured quantities were the current flowing through the short circuit, the voltage between the short-circuit electrodes, and the spectroscopic spectrum of the luminous plasma. These quantities were measured using an AC/DC current sensor (Hioki, CT6973), a high-voltage differential probe (Tektronix, P5205A), and a spectrometer (Hamamatsu Photonics, OPAL-Luxe), respectively. The optical fiber connected to the spectrometer was positioned at the center outside the observation window. The discharge luminescence behavior was recorded using a high-speed camera (nac Image Technology, MEMRECAM ACS-1 M60). The frame rate and shutter speed were set to 200,000 fps and 1/250,000 s, respectively. Current and voltage signals were recorded using a high-speed oscilloscope (Tektronix, MSO44 4-BW-1000). In this experiment, an external trigger signal was transmitted from the oscilloscope upon detection of the current signal, thereby synchronizing the start timing of the high-speed camera and the spectrometer.

As experimental conditions, the ambient gas species (nitrogen and air), ambient pressure (0.1–6.0 MPa), and ambient temperature (room temperature and 150 °C) were varied. For each combination of ambient gas species, ambient pressure, and ambient temperature, the short-circuit experiment was repeated 10 times for the inverter compressor and 60 times for the constant-speed compressor.

5.2.2 Numerical simulation method

The short-circuit phenomenon in the experimental system was reproduced using VizSpark v2.4.4 (Esgee Technologies, USA). Figure 5.2-4 shows a schematic of the simulation model. The computational domain was $3\ \mu\text{m} \times 6\ \mu\text{m}$, within which metal electrodes measuring $3\ \mu\text{m} \times 1\ \mu\text{m}$ were placed. The anode corresponded to the fixed electrode (SUS316), and the cathode corresponded to the movable electrode (copper). The fixed-electrode side was inclined by 10° to reproduce localized contact. Because the actual computational time was limited to $5\ \mu\text{s}$ owing to the computational load, the electrode moving speed was set to $0.2\ \text{m/s}$ so that the electrodes could come into contact within the computational time. An RC circuit was configured by connecting these electrodes to a DC power supply and a resistor. The power supply voltage was set to $250\ \text{VDC}$, and the resistance was set to $3.57\ \Omega$, thereby limiting the short-circuit current to $70\ \text{A}$. The gas surrounding the electrodes was air with an initial temperature of $300\ \text{K}$, and the initial pressure was set to $0.1, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0$, and $10.0\ \text{MPa}$.

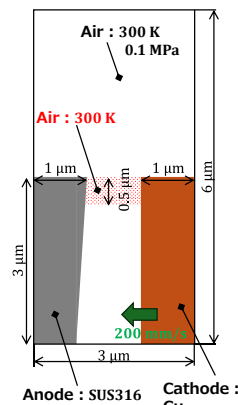


Figure 0-4 Schematic of the computational domain of the electrical short

5.3 Results and discussion

5.3.1 Experimental results of phase-to-phase short circuits in the inverter compressor (single-phase 200 V unit)

Figure 5.2-5 shows typical current and voltage waveforms before and after short-circuiting under an air atmosphere at room temperature and atmospheric pressure. From left to right, the results correspond to U-V, U-W, and V-W short circuits. In this experiment, recording was configured to begin when a trigger signal was issued after a current exceeding $30\ \text{A}$ flowed through the short circuit.

Immediately after short-circuiting ($t = 0\ \text{s}$), the voltage decreased, and a short-circuit current was generated. However, owing to the inductance of the motor coil, the short-circuit current did not increase instantaneously in response to the voltage change but rose with a slight delay. The voltage remained nearly constant at approximately $20\ \text{V}$ for approximately $12\ \mu\text{s}$, then momentarily increased again before decreasing to $0\ \text{V}$. By contrast, the current began to decrease almost linearly at approximately $2\ \mu\text{s}$ and reached zero after approximately $12\ \mu\text{s}$. Immediately after short circuiting, a low-resistance arc channel was formed between the electrodes, which had previously constituted an open circuit. Consequently, charge stored between the electrodes, in the windings, at the inverter output terminals, in the cables, and in other components was discharged at once, producing a pronounced spike. Subsequently, the inverter protection circuit is considered to have been activated as the current increased, producing another spike near the current peak. When the protection circuit operated fully, current and voltage both ceased; however, because the inductance acted to maintain the current at that instant, a counter electromotive force determined by the product of the inductance and current decay rate was generated, producing a large spike. Since the U, V, and W phases were shifted by 120° from one another (Ide, 2006),

the discharge waveform varied somewhat depending on the timing of discharge initiation. However, no strong dependence of the arc voltage or peak current on the short-circuited phase combination (U-V, U- W, or V-W) was observed.

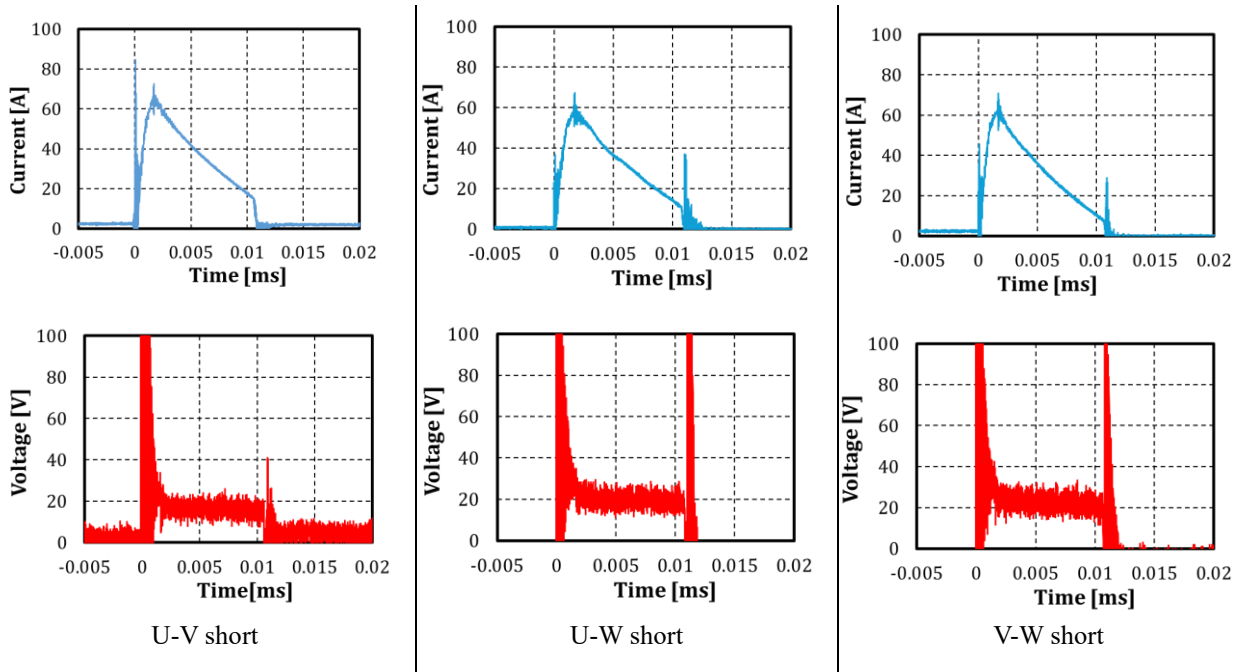


Figure 0-1 Typical waveforms of the phase-to-phase electrical short in the coil windings of the inverter-driven compressor of AC200 V RAC. Ambient conditions: air, room temperature, atmospheric pressure

Figure 5.2-6 shows representative current and voltage waveforms obtained for V-W short circuits under different ambient temperatures and pressures. Figure 5.2-7 shows the pressure dependence of the arc voltage, maximum current, and short-circuit discharge energy, calculated by integrating the product of the current and voltage waveforms over the discharge duration, with temperature used as the legend. Because the circuit was an inverter circuit, the current occasionally took negative values; in such cases, only the polarities of both current and voltage were reversed, whereas their absolute values remained nearly unchanged. This indicates that the current and voltage waveforms were scarcely affected by ambient temperature or pressure. The arc voltage was also approximately 20 V and showed little dependence on ambient pressure or temperature. In arc discharge, the electrode surface is heated to a high temperature and emits thermoelectrons, resulting in a high current density. Accordingly, the current and voltage waveforms are strongly related to the electrode temperature. Since the surrounding gas temperature was sufficiently low in comparison, its influence is considered to have been limited. Similarly, pressure is unlikely to increase the ambient temperature to a level comparable to the electrode temperature, and almost no pressure effect was observed. Consequently, the energy obtained by integrating the product of current and voltage over the discharge duration was also nearly independent of pressure, with a value of approximately 5–8 mJ.

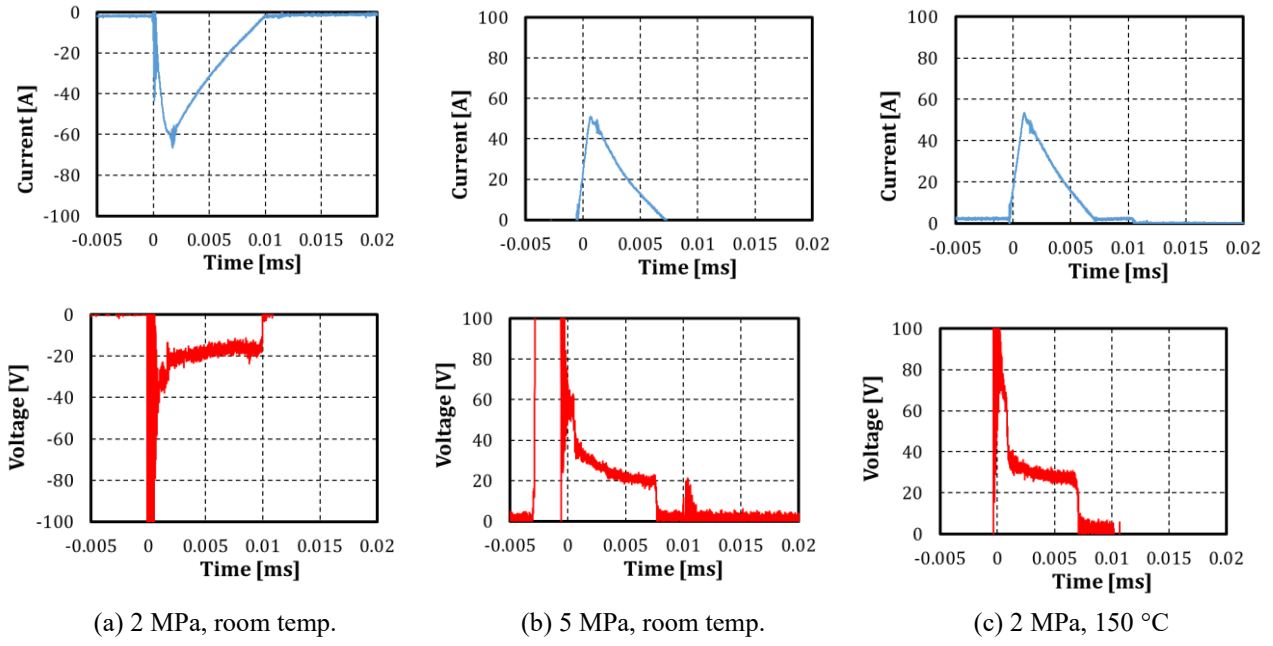


Figure 0-2 Typical waveforms of the V-W phase electrical short in the coil windings of the inverter-driven compressor of AC200 V RAC under different environmental conditions

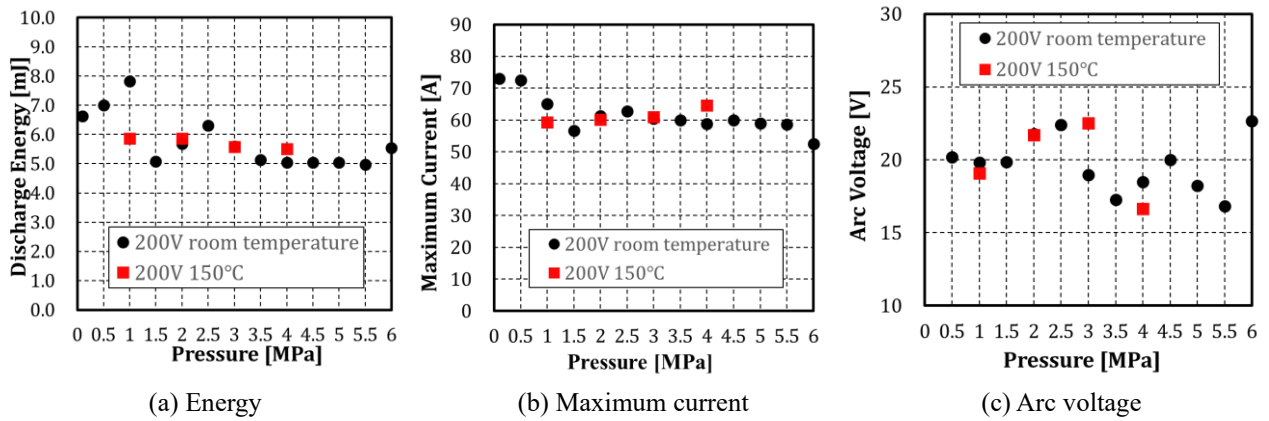


Figure 0-3 Dependence of the arc discharge energy, maximum current, and arc voltage on ambient pressure and temperature in the V-W phase electrical short of AC200 V RAC

Figure 5.2-8 shows an example of the discharge luminescence recorded during a V-W phase-to-phase short circuit. As the ambient pressure and temperature increased, the discharge luminescence region tended to expand. In particular, the effect of increasing the temperature was pronounced: even at the same ambient pressure, the luminescence region clearly expanded under a temperature of 150 °C. This is attributable to an increase in the number of molecules with increasing initial pressure and to the enhanced molecular motion caused by the temperature increase, which allowed excited molecules to diffuse over a wider region.

However, this result appears inconsistent with the finding that discharge energy changed slightly with pressure or temperature. Therefore, the temperature was estimated by spectroscopic analysis of the emission spectrum associated with the discharge, and the corresponding energy was subsequently estimated. The Boltzmann method was used for temperature estimation. This method is based on the fact that the populations of excited atomic and molecular states in plasma follow the Boltzmann distribution. When the number of particles in the upper level is denoted by n_u , the total number of particles by n , the degeneracy by g_u , the Boltzmann constant by k_B , the upper-level energy by E_u , the

temperature-dependent partition function by $Z(T)$, and the excitation temperature by T_{exc} , the following equation is obtained:

$$\frac{n_u}{n} = \frac{g_u}{Z(T)} \exp\left(-\frac{E_u}{k_B T_{exc}}\right). \quad (5.3-1)$$

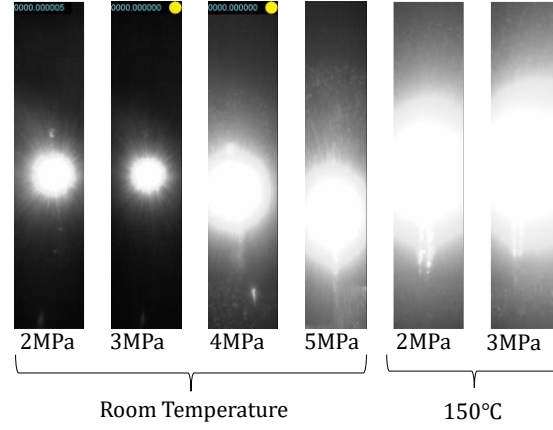


Figure 0-4 Luminescence of the discharge generated by the V-W phase electric short under different ambient conditions

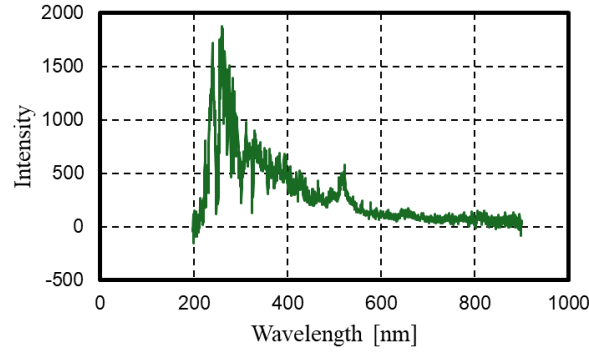


Figure 0-5 Example of the plasma spectrum generated by the V-W phase electrical short

The emission intensity I_{ul} of the spectral line generated when the energy level decreases from u to l is expressed by the following equation, where A_{ul} is the Einstein coefficient and $h\nu$ is the transition energy.

$$I_{ul} \propto n_u \cdot A_{ul} \cdot h\nu \quad (5.3-2)$$

From Equations. (5.3-1) and (5.3-2), the following equation is obtained:

$$I_{ul} \propto \frac{g_u A_{ul}}{Z(T)} \exp\left(-\frac{E_u}{k_B T_{exc}}\right). \quad (5.3-3)$$

Taking the logarithm of both sides of Equation (5.3-3) gives Equation (5.3-4).

$$\ln \frac{(I_{ul} \lambda)}{g_u A_{ul}} = -\frac{E_u}{k_B T_{exc}} + \text{const.} \quad (5.3-4)$$

Therefore, when I_{ul} , E_u , g_u , A_{ul} at wavelength λ are identified from the spectroscopic spectrum using sources such as the NIST database (NIST, 2024), T_{exc} can be obtained from the slope of Equation (5.3-4). An example of the measured emission spectrum (ambient gas: nitrogen; 4 MPa; room temperature) is shown in Figure 5.2-9. Applying the above

method to this spectrum yielded $T_{exc} \cong 10^4$ K. Previous studies have reported that when the excitation temperature is $10^4 \sim 10^5$ K, the gas temperature is approximately $T_{gas} = 10^2 \sim 10^3$ K (Buggeman *et al.*, 2014; Sintsov *et al.*, 2020; Xu *et al.*, 2013). Therefore, an empirical equation relating the excitation temperature to the gas temperature was derived from the literature and used for estimation. The estimated gas temperature was approximately 500 K at 1.0 and 2.0 MPa under room-temperature conditions and approximately 1500 K at 4.0 and 5.0 MPa. Nearly identical values were obtained under the 150 °C condition. If the energy possessed by the plasma is expressed as the product of the thermal energy emitted per unit time from the plasma body and its duration, it is given by the following equation, where t_{peak} [s] is the time required for the plasma to reach its maximum diameter, T_{∞} [K] is the ambient temperature, ρ [kg/m³] is the gas density, d [m] is the maximum plasma diameter, c_p [J/(kgK)] is the specific heat, and t_l [s] is the plasma duration.

$$E = \frac{T_{gas} - T_{\infty}}{t_{peak}} \cdot \rho \cdot c_p \cdot \frac{1}{6} \pi d^3 \cdot t_l \quad (5.3-5)$$

The values of d and t_{peak}, t_l were read from the acquired images, and the energy was calculated using Equation (5.3-5) together with the value of T_{gas} obtained above. As shown in Table 5.2-2, the calculated energies were 112 mJ at 2.0 MPa and 703 mJ at 5.0 MPa, more than two orders of magnitude larger than the measured values. In this calculation, the entire luminescence region was assumed to have a temperature equal to T_{gas} . However, because the discharge duration was extremely short, the entire plasma was unlikely to reach thermal equilibrium. Furthermore, regions other than the central portion, with a diameter of approximately 1 mm, are considered to exhibit chemiluminescence associated with excitation without a corresponding temperature rise (Tao *et al.*, 2024). Therefore, the plasma region at T_{gas} was recalculated by assuming a diameter of 1 mm. The results are outlined in the lower part of Table 5.2-2. These values are generally consistent with the experimental results, indicating that short-circuit discharge energy may be estimated by analyzing the spectroscopic spectrum of the plasma.

Table 0-1 List of calculated plasma energy generated by the V-W phase electrical short estimated by the spectroscopy analysis using Equation (5.3-5)

	2.0MPa, room temp.	5.0MPa, room temp.	2.0MPa, 150°C
Assuming that temperature in all luminous region corresponds to T_{gas}	112 mJ	703 mJ	583 mJ
Assuming that temperature in only 1 mm diameter of plasma corresponds to T_{gas}	4.2 mJ	5.6 mJ	1.7 mJ

5.3.2 Experimental results of phase-to-phase short circuits in the inverter compressor (single-phase 100 V unit)

Figure 5.2-10 shows an example of discharge waveforms during V-W short circuiting in the single-phase 100 V unit. The waveform is almost the same as that observed for the single-phase 200 V unit. This indicates that the arc discharge voltage is determined primarily by the electrode material rather than the power supply voltage. Figure 5.2-11 shows the dependences of arc voltage, maximum current, and energy on the initial pressure. Data for the 200 V unit are also shown for comparison; however, no clear change in trend was observed between the 100 and 200 V units. Therefore, even in the single-phase 100 V unit, the discharge characteristics during a phase-to-phase short circuit are nearly the same as those of the single-phase 200 V unit described in (a).

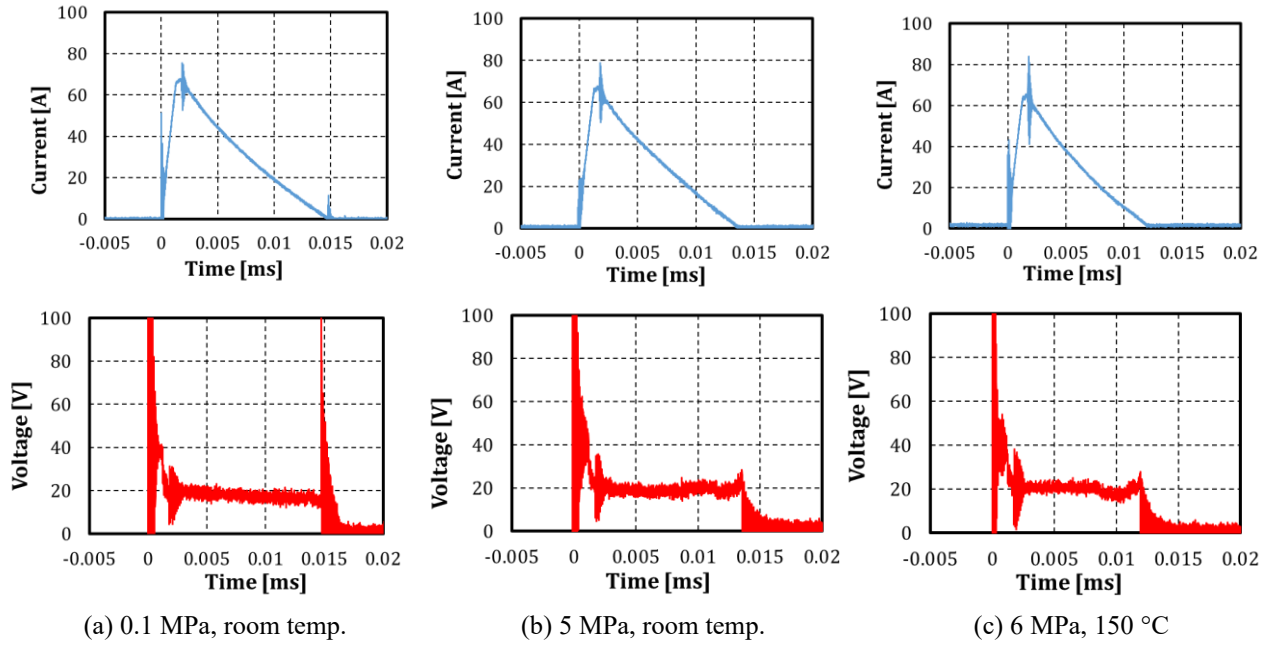


Figure 0-6 Typical waveforms of the V-W phase electrical short in the coil windings of the inverter-driven compressor of AC100 V RAC under different environment conditions

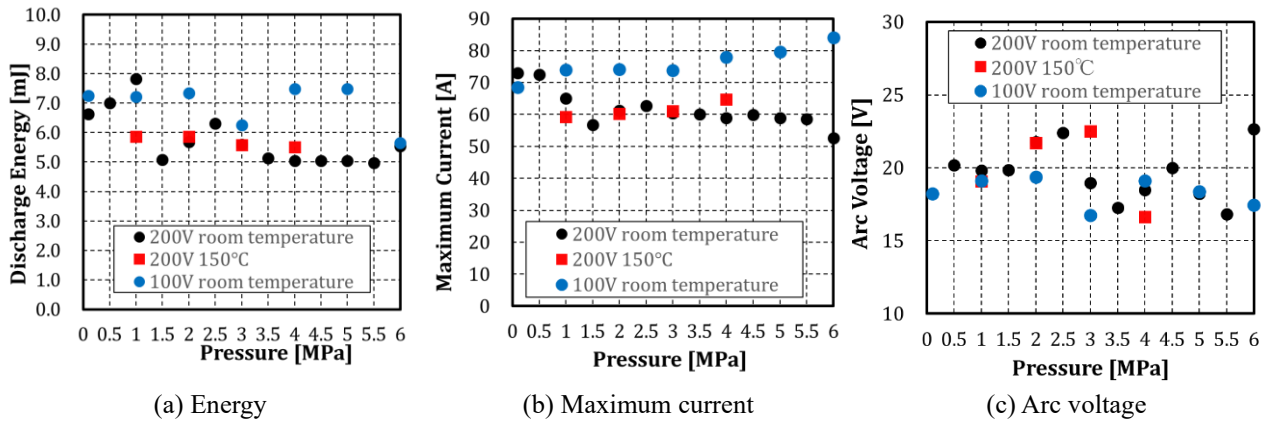


Figure 0-7 Dependence of the arc discharge energy, maximum current, and arc voltage on ambient pressure and temperature in the V-W phase electrical short of AC200 V and AC100 V RAC

5.3.3 Experimental results of phase-to-phase short circuits in the constant-speed compressor

Figure 5.2-12 shows representative current and voltage waveforms obtained using the single-phase 100 V constant-speed compressor. The ambient conditions were air at room temperature and atmospheric pressure. Unlike the inverter compressor, periodic current spikes and sawtooth-like voltage waveforms were observed. In addition, no regularity was found in the number of discharge events. Although each discharge lasted approximately 20 μ s, repeated discharges lasting approximately 5 ms were observed when multiple discharges occurred. In a constant-speed compressor, commercial power (AC100 V, 60 Hz in the present experiment) is supplied directly to the motor; therefore, the power supply phase at the moment of short-circuiting varies from test to test. This variation strongly affects the current and voltage waveforms and the short-circuit energy. Because no current initially flows through the short circuit, a large current flows, and plasma is generated when short-circuiting occurs at high voltage. This plasma is cooled through collisions with the electrodes and heat loss to the surrounding fluid; after a certain period, it is extinguished and the current becomes zero. However, a

counter electromotive force is generated by the motor inductance, causing the voltage to increase again. When this voltage exceeds the arc voltage, reignition occurs. Thus, when short-circuiting occurs at a power supply phase of approximately 90–120°, the discharge energy tends to be relatively large. By contrast, when short-circuiting occurs near the zero crossing, the short-circuit current is small, the arc is extinguished quickly, and the counter electromotive force is also small; consequently, the voltage does not reach the level required for reignition. As such, we conclude that only a small discharge occurs, and the discharge energy depends strongly on the power supply phase and the energy stored in the motor. This interpretation is supported by the relationship between the voltage at the moment of short-circuiting and the maximum current and discharge energy of the first spark waveform observed at that instant (Figure 5.2-13). As indicated by Ohm's law, the maximum current was proportional to the voltage at short-circuiting, and the energy was proportional to the square of that voltage.

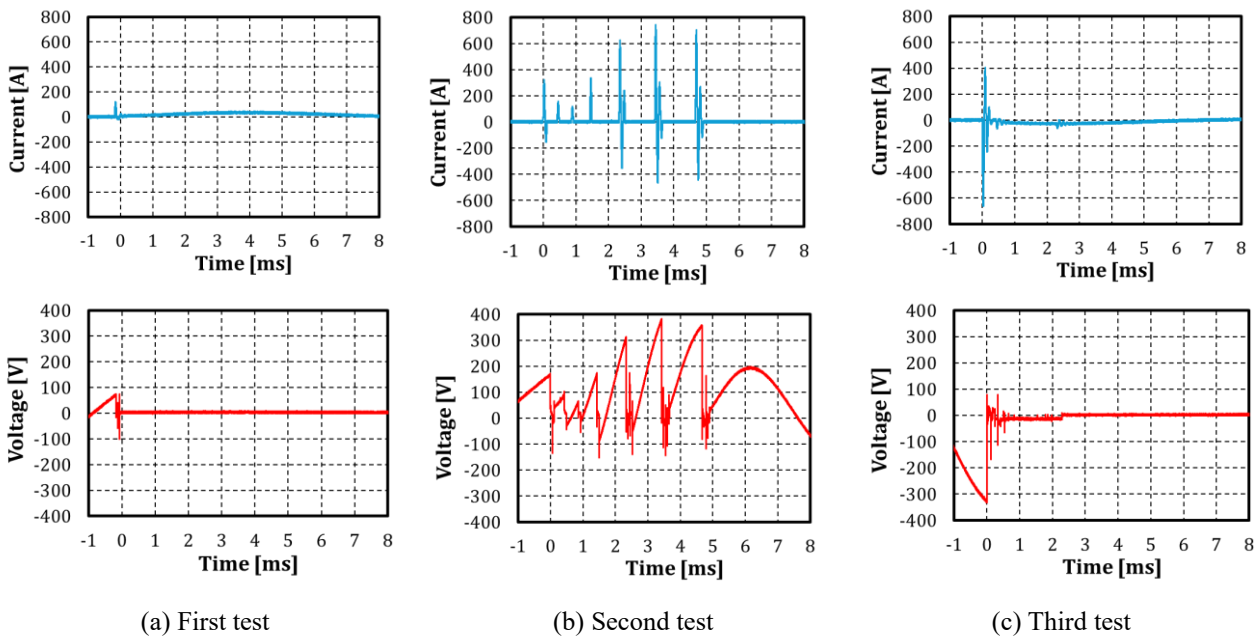


Figure 0-8 Typical waveforms of the V-X phase electrical short of the constant-speed compressor of the AC100 V refrigerator. Ambient: air, atmospheric pressure, room temperature

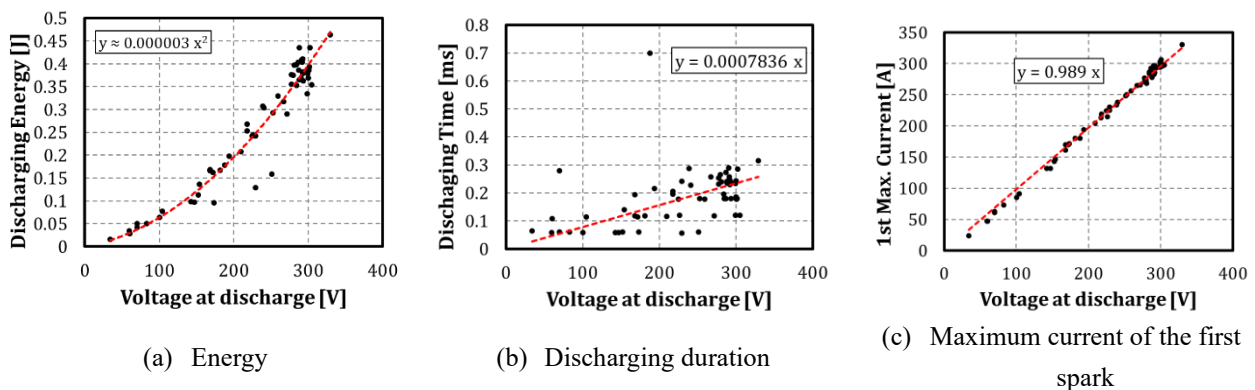


Figure 0-9 Dependence of the energy, maximum current, and discharging time on the voltage at the beginning of the electrical short

In addition, because no inverter element is present, the time required for current interruption when a large flow of current exists is determined by the capacity of the overcurrent breaker installed in the circuit; therefore, the discharge

duration is considered to have been much longer than that in the inverter compressor ($0.01 \text{ ms} \rightarrow 5 \text{ ms}$). In the present experiment, the capacity of the overcurrent breaker installed in the constant-speed compressor was 30 A. The energy obtained by integrating the product of current and voltage over the discharge duration was 3.8 J on average, with a maximum of 6.9 J and a minimum of 0.81 J.

Figure 5.2-14 shows the discharge behavior during short-circuiting. Compared with the single-phase 200 V inverter compressor (Figure 5.2-8), the luminescence region was considerably larger. Conversely, although the emission spectrum shown in Figure 5.2-15 had a higher intensity than that of the single-phase 200 V unit, the peak wavelengths were almost the same, suggesting that the elemental components contained in the plasma were nearly identical.

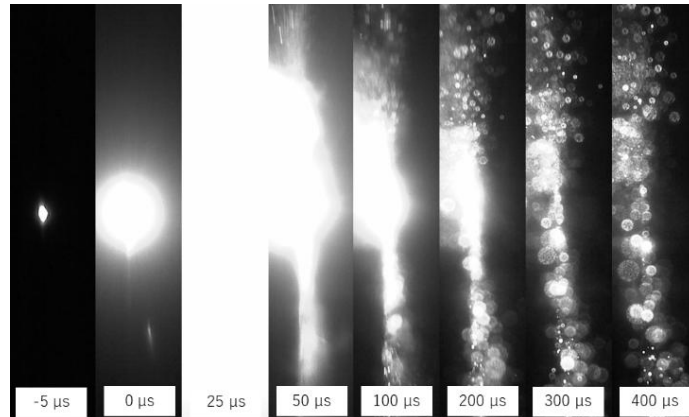


Figure 0-10 Luminescence of the discharge generated by the V-X phase electric short of the constant-speed compressor

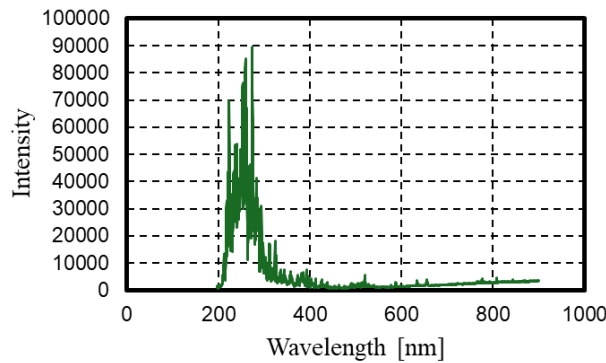


Figure 0-11 Example of the plasma spectrum generated by the V-X phase electrical short of the constant-speed compressor

5.3.4 Numerical simulation results for phase-to-phase short circuits in the inverter compressor

Figure 5.2-16 shows the simulated temperature and current density distributions before and after discharge. The vessel pressure was set to 1.0 MPa. In each case, the temperature distribution is shown on the left and the current density distribution on the right. The temperature distribution indicates that an arc was formed at the upper end of the electrode when discharge began. The current density distribution shows that, before discharge initiation, a weak current density gradient was generated from the upper to the lower end of the electrode owing to glow discharge; immediately after discharge initiation, the current density at the upper end of the electrode increased rapidly.

Figure 5.2-17 shows the time evolutions of current, voltage, and power, calculated as the product of current and voltage, at vessel pressures of 0.1, 5.0, and 10.0 MPa. The instant at which the voltage changed sharply (because the voltage was

negative, this corresponds to a decrease in the absolute value, thereby indicating a voltage drop accompanied by current generation) did not correspond to arc short-circuit initiation; this timing varied with the initial pressure. However, it did not vary monotonically with pressure. The time required for short-circuiting was shortest at 0.1 MPa and longest at 0.5 MPa, where short-circuiting was most difficult. At 10 MPa, the time was longer than that at 0.1 MPa but shorter than that at 0.5 MPa.

Figure 5.2-18 compares the discharge energy obtained from the simulation with the measured values. The filled circles indicate the values obtained by integrating the product of current and voltage from the start to the end of discharge, whereas the open circles indicate the values obtained by limiting the integration interval to the period after arc discharge initiation. When only the energy associated with arc discharge was considered, the pressure at which the energy reached a minimum was observed. This trend is consistent with the relationship between the arc initiation time and the pressure described above and suggests that the arc initiation conditions are affected by the interaction between the pressure-induced inhibition of thermoelectron motion from the electrode and electron avalanche caused by the increase in the number of molecules with increasing pressure. Overall, the energy was nearly independent of pressure, and the experimental results were well reproduced.

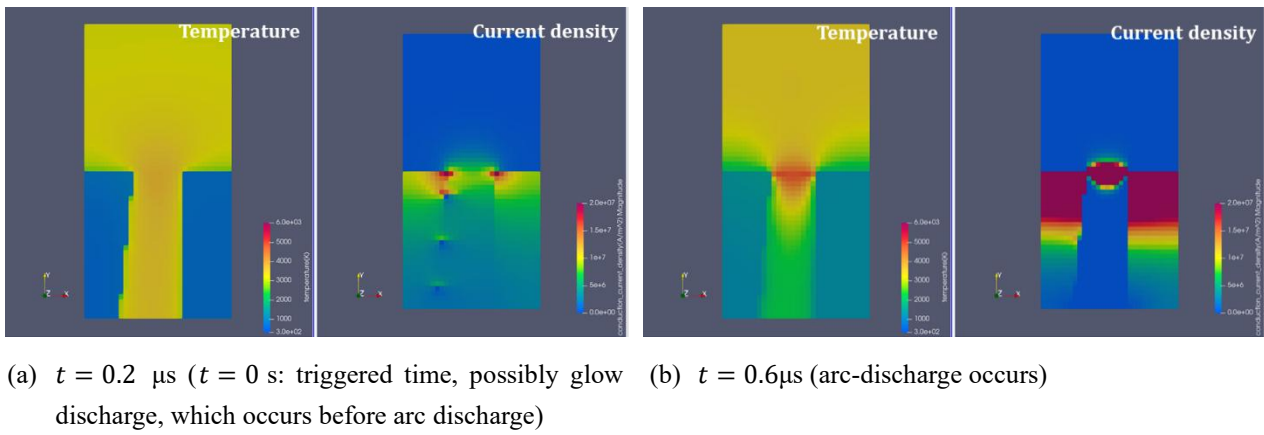


Figure 0-12 Typical contours of temperature distribution and current density

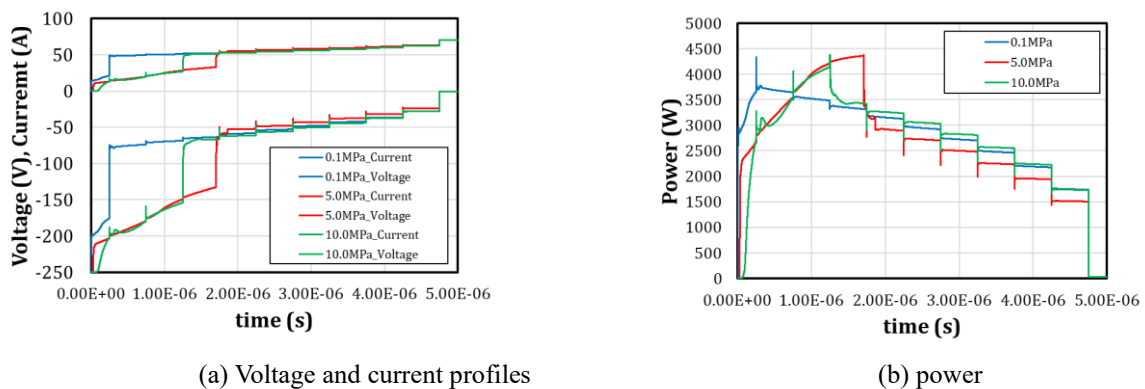


Figure 0-13 Time evolutions of voltage, current, and power obtained by numerical simulation

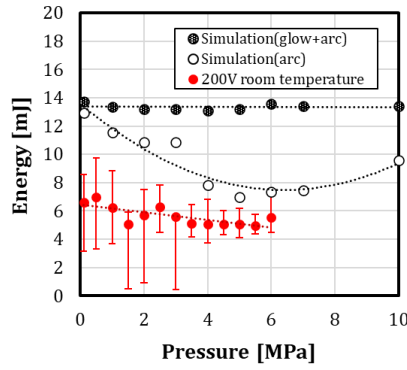


Figure 0-14 Comparison of the dependence of the arc discharge energy on pressure obtained by experiment and simulation

5.4 Summary and future work

In this study, the arc discharge energy that may be generated during phase-to-phase short circuits and ground faults in inverter-driven and constant-speed compressors was quantified through FY2025 using a combined approach based on experiments, numerical simulations, and theoretical considerations. In the experiments, an apparatus was developed in which the lead wires of commercially available inverter compressor units and an actual constant-speed compressor unit were extended and connected to a short-circuit device, enabling short-circuit tests under high-temperature and high-pressure environments. Using this apparatus, short-circuit tests were conducted, current and voltage waveforms were measured to determine energy, and energy was also estimated from the spectroscopic analysis of emission spectra generated by discharge. In addition, numerical simulations were used to reproduce the phenomenon and to develop a method for predicting the discharge energy.

For phase-to-phase short circuits in the inverter compressor, arc discharge generally occurred as a single pulse with a discharge duration of approximately 12 μs , and the arc discharge energy was approximately 5–8 mJ. The results showed that the effects of ambient pressure, temperature, and power supply specifications were limited and that the energy depended primarily on the material of the short-circuit electrodes. Although the discharge luminescence region expanded with increasing pressure and temperature, spectroscopic analysis demonstrated that the estimated energy was of the same order as the experimentally measured energy.

For phase-to-phase short circuits in the constant-speed compressor, the current and voltage waveforms varied across each test, unlike those observed in the inverter compressor. This variation occurred because the compressor and power supply were directly connected, causing the discharge behavior to depend on the power supply phase at the moment of short-circuiting. Consequently, the discharge duration was longer, and the arc discharge energy was orders of magnitude larger than that of the inverter compressor, with an average value of 3.8 J.

Based on these results, a model for estimating the arc discharge energy during phase-to-phase short circuits in the inverter compressor was constructed. Substituting representative numerical values into the model yielded good agreement with the experimental results. The numerical simulations also demonstrated that the phenomenon could be reproduced computationally.

Expansion of the dataset for the constant-speed compressor will continue in future work, and arc discharge energy prediction models applicable to both inverter-driven and constant-speed compressors will be developed. In addition, experiments and investigations will be conducted to quantify the energy associated with sliding friction and other factors that are expected to act as potential sources of energy generation inside compressors, in addition to arc discharge.

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APPENDIX: Safety Evaluation in Actual Use of Refrigerants With the Potential for Self-Decomposition Reactions (The Japan Refrigeration and Air Conditioning Industry Association)

The Self-Decomposition Reaction Risk Study Working Group (hereinafter, the “WG”) of the Japan Refrigeration and Air Conditioning Industry Association (hereinafter, “JRAIA”) conducted a safety evaluation of the practical use of refrigerants with the potential for self-decomposition reactions that are being examined as NEDO green refrigerants. The study aimed to assess the risks associated with using refrigerant mixtures containing ethylene-based HFOs in refrigeration and air conditioning equipment to examine the measures required to ensure safety and identify conditions under which self-decomposition reactions can be avoided while equipment safety is maintained. A further objective is to disseminate, at an early stage, the prospect that NEDO green refrigerants can be used safely without inducing self-decomposition reactions, thereby encouraging stakeholders to consider these refrigerants.

In fiscal year 2022, JRAIA established the “Preparatory WG for the Study of Self-Decomposition Reaction Risk” and conducted activities to examine methods for the risk assessment of refrigerants with the potential for self-decomposition reactions. Building on the knowledge obtained by the predecessor preparatory WG, the organization has now formally commenced full-scale activities, from December 2023, as the “Self-Decomposition Reaction Risk Study WG,” in coordination with the NEDO Study Group on Self-Decomposition Reactions.

With respect to ensuring safety, the WG mainly examined scenarios in actual equipment that could exceed the boundary conditions for the occurrence and propagation of self-decomposition reactions, as well as the probabilities of their occurrence, based on the boundary conditions for the occurrence and propagation of self-decomposition reactions provided by the NEDO Study Group on Self-Decomposition Reactions and refrigerant manufacturers.

In addition, the prospect of using these refrigerants while avoiding self-decomposition reactions and the range of equipment specifications for which such use is feasible were presented at the NEDO Project Activity Report Meeting and at the International Symposium on Environment and New Refrigerants 2025.

A.1 Self-decomposition reactions

The ethylene-based HFO refrigerants examined in this study, such as R1132(E), possess the property of undergoing a self-decomposition reaction known as disproportionation. A self-decomposition reaction is a decomposition reaction in which the same substance undergoes both oxidation and reduction, and it is characterized by the fact that the reaction can proceed even in the absence of air. This reaction begins when energy exceeding a certain threshold is applied to the refrigerant. Because the reaction is exothermic, it propagates in a chain reaction under temperature and pressure conditions that exceed the relevant boundary conditions. If such a reaction occurs inside a compressor, the resulting increase in internal temperature and pressure may cause compressor rupture.

For R1132(E) alone, the temperature and pressure boundary conditions under which the self-decomposition reaction propagates fall within the conditions normally used in refrigeration cycles. As such, using R1132(E) alone is challenging. However, by blending R1132(E) with other refrigerants, thereby diluting R1132(E), the reaction boundary conditions can be shifted toward a higher temperature and pressure. The refrigerants targeted in this study are those in which the reaction boundary conditions have been shifted to a higher temperature and higher pressure than the operating conditions used in equipment by blending R1132(E) with R1234yf and/or R32. In particular, the two-component refrigerants R474A and R474B are mixtures of R1132(E) and R1234yf, whereas the three-component refrigerant R479A is a mixture of R1132(E), R1234yf, and R32.

A.1.1 Self-decomposition reaction limit

The combination of temperature and pressure, which constitutes the boundary conditions for the occurrence of a self-decomposition reaction, varies depending on the energy applied to the refrigerant to initiate the reaction (hereinafter, the “input energy”) and on the blending composition of the refrigerant (i.e., the proportion of R1132(E)). Figure A.A.1-1 illustrates this concept. In the figure, each graph shows the relationship between the temperature and pressure at which a self-decomposition reaction occurs, with (a) representing the basic pattern. The curve drawn from the upper left to the right side of the figure is the boundary line of the temperature and pressure at which the self-decomposition reaction occurs and propagates (hereinafter, the “self-decomposition reaction limit line”). In the region above this line, self-decomposition reactions occur and propagate (hereinafter, the “self-decomposition reaction region”). As noted above, the self-decomposition reaction limit line varies according to the input energy and the refrigerant composition. Figure (b) shows the conceptual change in the self-decomposition reaction limit line when the input energy changes. As the input energy increases, the self-decomposition reaction limit line shifts toward a lower temperature and pressure, making self-decomposition reactions more likely to occur. Conversely, when the input energy is smaller, the self-decomposition reaction limit line shifts toward a higher temperature and pressure. Figure (c) shows the conceptual change in the self-decomposition reaction limit line when the proportion of R1132(E) in the refrigerant changes. As the proportion of R1132(E) increases, the self-decomposition reaction limit line shifts toward a lower temperature and pressure, making self-decomposition reactions more likely to occur.

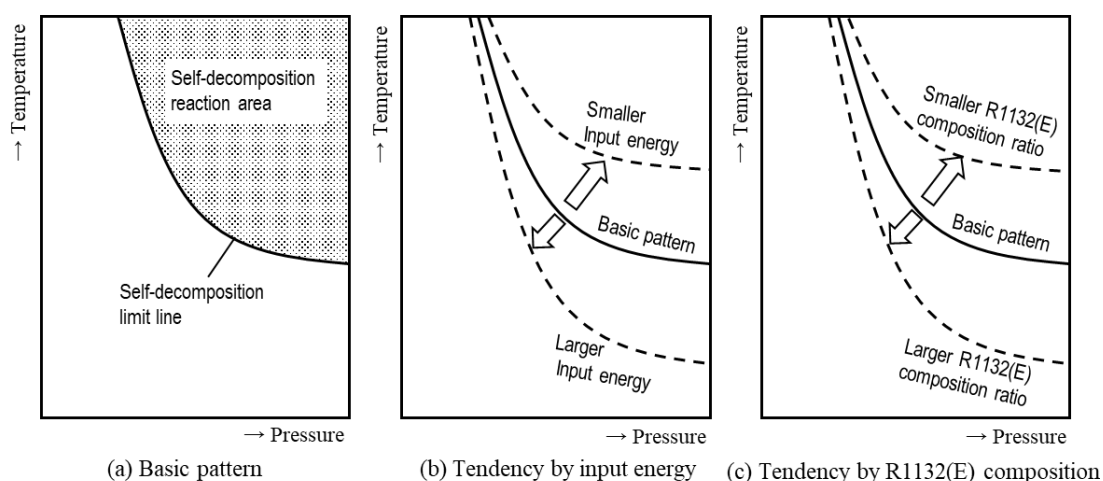


Figure A.A.1-1 Conceptual diagram of the self-decomposition reaction limit.

A.1.2 Concept of the conditions for the occurrence of self-decomposition reactions in actual equipment

The relationship between the conditions for the occurrence of self-decomposition reactions described above and the possibility of these reactions occurring in actual refrigeration and air conditioning equipment is explained below. First, the compositions of the three refrigerant mixtures targeted in this study (R474A, R474B, and R479A) are designed such that self-decomposition reactions do not occur under the temperature and pressure conditions used during the normal operation of refrigeration and air conditioning equipment, nor under the temperature and pressure conditions corresponding to the margin before protection initiates when the normal operating range is exceeded for some reason. Therefore, if refrigeration and air conditioning equipment is operating normally or the protective functions are operating properly, no possibility of self-decomposition reactions occurring exists. However, because equipment may enter

abnormal operating conditions and the protective functions may fail to operate at that time, the equipment operating conditions may exceed the protection margin range, reach high temperature and pressure, and cross the self-decomposition reaction limit line.

Next, regarding the input energy in refrigeration and air conditioning equipment, the principal energy source is a short circuit of the motor installed inside the compressor. The input energy generated at that time differs depending on the short-circuit mode of the motor and the power-supply specification. As the input energy increases, the self-decomposition reaction limit line shifts toward a lower temperature and pressure, which may make self-decomposition reactions more likely to occur.

The refrigerant mixtures targeted in this study are zeotropic refrigerants; therefore, they exhibit a temperature glide. Because the composition of a zeotropic refrigerant changes within the refrigeration cycle, the proportion of R1132(E) may locally increase, shifting the self-decomposition reaction limit line toward a lower temperature and pressure and making self-decomposition reactions more likely to occur.

Because each of the above factors affects the occurrence of self-decomposition reactions in a combined manner, the key point in risk assessment is to determine the range of influence of each factor and how to relate them to each other in considering the possibility of self-decomposition reactions occurring. This concept is explained in A.2.

A.2 Framework for self-decomposition reaction risk assessment

A self-decomposition reaction is initiated by an energy input, such as a short circuit in the compressor motor, and subsequently propagates under high-temperature and high-pressure conditions. The following risk-assessment items were established to address, in an integrated manner, scenarios in which such energy inputs are generated and high-temperature/high-pressure conditions arise, to determine whether self-decomposition reactions occur under the conditions reachable in those scenarios, and to estimate the probability of their occurrence.

A.2.1 Risk assessment item 1 (basic form)

The basic form of self-decomposition reaction risk assessment comprises the following items ①–④:

- ① Extraction of scenarios that may lead to high temperature and high pressure
In refrigeration and air conditioning equipment, scenarios where the internal temperature or pressure within the refrigeration cycle may become high are extracted, including abnormal operating states.
- ② Investigation of the reachable conditions for each scenario
For the scenarios extracted in ① above, the reachable temperature and pressure conditions are confirmed by actual equipment testing.
- ③ Determination of hazardous scenarios
This process involves confirming whether the reachable conditions of each scenario verified in ② above exceed the self-decomposition reaction limit line and enter the self-decomposition reaction region; if they do, the scenario is determined to be hazardous.
- ④ Estimation of the probability of hazardous scenarios (FTA)
For the scenarios determined to be hazardous in ③ above, FTA is conducted to estimate the probability of occurrence for each scenario. If the resulting probability exceeds the acceptable probability (1×10^{-10} or less), measures are implemented to reduce it, and then the FTA is repeated.

A.2.2 Risk assessment item 2 (related to the self-decomposition reaction limit line; examination for

identifying the usable range)

As an activity of the JRAIA WG, it is considered necessary to obtain, at an early stage, a prospect for whether self-decomposition reactions can be avoided for the target refrigerants and to disseminate that information to stakeholders, thereby creating an environment where manufacturers can begin considering the target refrigerants early on. However, determining whether each scenario is hazardous for each individual equipment specification would require numerous case distinctions. In addition, preparing self-decomposition reaction limit lines that comprehensively cover all input energies and R1132(E) composition ratios would require an enormous number of tests and thus a considerable amount of time.

Accordingly, it was decided that refrigerant manufacturers would prepare self-decomposition reaction limit lines using the maximum conceivable input energy (i.e., the condition under which self-decomposition reactions are most likely to occur) and with the R1132(E) composition ratio varied in increments of 5%. Estimates of the maximum input energy and the range over which the composition ratio of R1132(E) may change were made.

In addition, the maximum R1132(E) composition ratio at which self-decomposition reactions do not occur under the reachable temperature and pressure conditions of all scenarios confirmed in this study was defined as the “R1132(E) limiting composition ratio.” By back-calculating the equipment-specification-side conditions that do not exceed this limiting composition ratio, we aimed to indicate the range of equipment specifications in which self-decomposition reactions can be avoided even without implementing special countermeasures for preventing self-decomposition reactions.

The implementation items for these examinations are shown below as items ⑤–⑨.

⑤ Estimation of the maximum input energy

The maximum input energy of inverter-driven equipment is estimated from the measured results of the input energy in inverter systems.

⑥ Estimation of the maximum R1132(E) composition ratio

The maximum R1132(E) composition ratio within the operating-environment temperature range of the equipment is estimated, together with the equipment specifications that strongly affect the possibility that the target refrigerant may undergo a change in circulating composition within the refrigeration cycle.

⑦ Estimation of the self-decomposition reaction limit line

Based on the maximum input energy estimated in ⑤ above, refrigerant manufacturers prepare self-decomposition reaction limit lines at 5% increments of the R1132(E) composition ratio.

⑧ Setting the R1132(E) limiting composition ratio

Among the self-decomposition reaction limit lines prepared at 5% increments of the R1132(E) composition ratio, as estimated in ⑦ above, the maximum R1132(E) composition ratio for which all scenarios do not exceed the self-decomposition reaction limit line is defined as the R1132(E) limiting composition ratio.

⑨ Identification of equipment-specification conditions that do not exceed the R1132(E) limiting composition ratio

Based on the study results in ⑥ above, the range that does not exceed the R1132(E)-limiting composition ratio defined in ⑧ is identified for each refrigerant, using the ratio of the amount of refrigerant that may remain in the accumulator to the amount of refrigerant charge.

A.3 Self-decomposition reaction scenarios and examination of reachable conditions

Potential self-decomposition scenarios were identified as operating states in which refrigeration and air conditioning equipment may experience high temperature and high pressure. As a practical benchmark, the temperature and pressure range ordinarily permitted during normal operation for different equipment types is approximately up to 120 °C and 4 MPa. Allowing for the protection margin beyond this range, scenarios capable of exceeding 150 °C or 6 MPa were selected for detailed examination.

These temperature and pressure conditions may appear when an abnormality occurs in the equipment and, in addition, some or multiple protective functions do not operate. Within the Self-Decomposition Reaction Risk Study WG, a total of 65 scenarios were proposed, including scenarios that had been extracted by the predecessor Preparatory WG for the Study of Self-Decomposition Reaction Risk.

Based on the phenomena occurring in the proposed scenarios, similar scenarios were organized and classified into several categories, and for 19 scenarios considered likely to reach comparatively high temperatures and pressures within those categories, verification tests of the reachable conditions were performed by sharing the work among the manufacturers. These results are presented later in A.6.

A.4 Estimation of the maximum input energy

Because the energy generated by a motor short circuit in a compressor directly affects the self-decomposition reaction limit, it is one of the dominant factors governing the occurrence of self-decomposition reactions. This input energy varies substantially with short-circuit location, short-circuit mode, timing, and other factors. The WG avoided underestimating the associated risk by estimating the maximum input energy and adopting it as a principal basis for determining whether self-decomposition reactions may occur.

Although the input energy is expected to differ significantly depending on the power-supply method, the present study estimated the maximum input energy for inverter-driven equipment, which is currently widely used in refrigeration and air conditioning equipment. In addition, because previous NEDO research observed that, for the same order of input energy, the discharge method more readily induced self-decomposition reactions than the fine-wire fusing method, the discharge energy was selected as the target of the present examination.

A.4.1 Measurement of the discharge energy in an inverter for RAC

Actual measurements of the discharge energy generated when a short circuit occurs in inverter-driven equipment were performed. Because the circuit configuration and protection specifications of inverters for domestic air conditioners (RACs) differ between manufacturers, single-phase 100 V inverters for 2.2 kW RACs supplied by WG member companies were used, and discharge energy measurements were performed to simulate the occurrence of a motor short circuit. Since motor short circuits include both phase-to-phase short circuits and ground faults, tests were conducted for both cases. The circuit diagrams are shown in Figure A.A.4-1.

In the figure, panel (a) assumes a phase-to-phase short circuit and panel (b) assumes a ground fault; the short circuit was produced by bringing a bare wire or an iron plate installed in part of the circuit into contact. The discharge energy was calculated based on the voltage and current at the time of contact and the duration of the event.

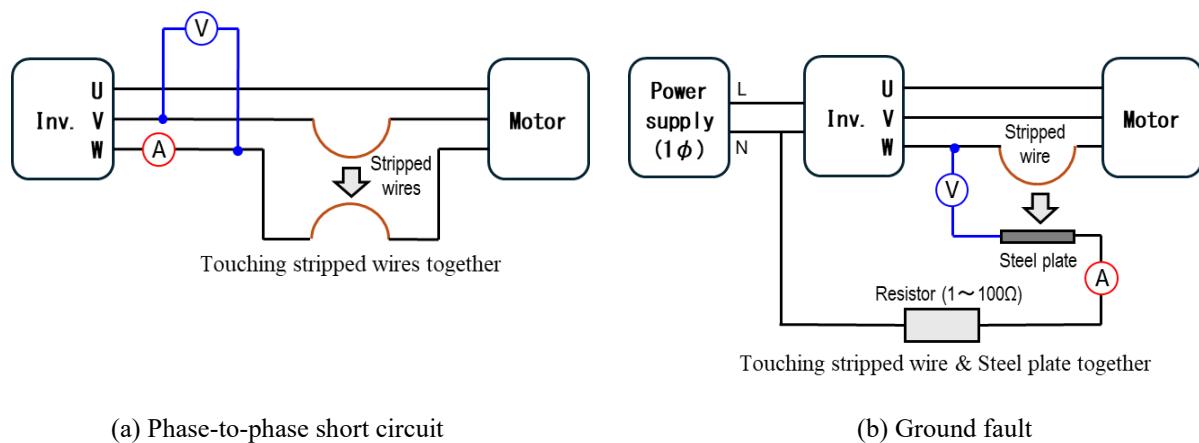


Figure A.A.4-1 Circuit for measuring the input energy.

Table A.4-1 Results of the input-energy (discharge) measurements.

Short-circuit mode	Input energy
Phase-to-phase	< 10 mJ
Earth fault	< 200 mJ

Because the discharge energy varies significantly, primarily based on the timing at which the short circuit occurs, several tests were performed, and the maximum generated energy was taken as the representative value. The results are outlined in Table A.4A.4-1. We found that the generated energy for ground faults was larger than that for phase-to-phase short circuits and that the generated energy was below 200 mJ.

A.4.2 Setting the maximum input energy for inverters

The inverter tested in A.4.1 was for a 2.2 kW RAC and, therefore, represented one of the smaller output categories among refrigeration and air conditioning equipment. However, a factor-of-50 safety margin was provisionally applied to the measured value, and the provisional maximum input energy was set to 10 J to enable application to inverters used in a broad range of refrigeration and air conditioning equipment, including larger-capacity, 200 V power supplies, and three-phase power supplies.

In contrast to inverters, for which current protection can be achieved in a short time by control, the circuits of constant-speed equipment, which are connected directly to the power supply, are expected to rely on mechanical protection to interrupt the current during a short circuit; therefore, the energization time becomes longer than that in inverters, and the input energy is considered to increase. Accordingly, the 10 J value set in the present study is not intended to apply to constant-speed equipment. For constant-speed equipment, the input energy will be identified in future studies.

A.5 Estimation of the maximum R1132(E) composition ratio

Because the refrigerants considered in the present study—R474A, R474B, and R479A—are non-azeotropic refrigerant mixtures comprising components with different boiling points, the mixed composition ratio in each part of the cycle may change from the charged composition after being charged into the refrigeration cycle. As noted above, when the mixed composition changes, the temperature and pressure at the self-decomposition reaction limit also tend to change; therefore,

changes in composition must be considered in the risk assessment.

Simulations and related analyses for each refrigeration cycle would have to be performed to calculate the composition change with high accuracy; moreover, such calculations would be required for each self-decomposition-reaction scenario, resulting in an enormous workload. Conversely, if the objective is only to estimate the maximum composition change for each target refrigerant, it can be calculated using a simplified method based on the ratio of the amount of liquid refrigerant that can remain in the cycle to the refrigerant charge amount in the cycle. The maximum R1132(E) composition ratio, which is considered to make self-decomposition reactions most likely to occur, was estimated using the following method.

A.5.1 Concept of a simplified estimation of composition change

Potential locations within the refrigeration cycle where composition change may occur are places where liquid refrigerant accumulates without circulating; the composition changes between the gas and liquid phases, and the composition ratio of R1132(E), which is the higher-pressure component, tends to increase in the gas phase and decrease in the liquid phase. Possible places within the refrigeration cycle where liquid refrigerant may accumulate include a high-pressure receiver, a medium-pressure receiver, an accumulator (low-pressure receiver), and the heat exchanger of a non-operating indoor unit in multi-split systems. The present study focuses on the composition change, which tends to increase the composition ratio of R1132(E) at the outlet of a liquid-refrigerant accumulating portion—that is, the composition change that tends to make self-decomposition reactions more likely to occur—and the tendency of composition change at each liquid-refrigerant accumulating portion is also considered.

First, the receiver is considered. In a high-pressure receiver, the outlet is a liquid refrigerant, and, therefore, the R1132(E) component is not expected to increase. In a medium-pressure receiver, the outlet is a two-phase refrigerant, and, thus, composition change tends not to occur readily. In an accumulator, the outlet is a gaseous refrigerant, and, therefore, the composition ratio of R1132(E) tends to increase.

Next, the heat exchanger is considered. When a refrigerant is circulating within the heat exchanger, the liquid refrigerant is flowing continuously. As such, composition change does not occur readily. A case in which a liquid refrigerant may accumulate in a heat exchanger is a non-operating indoor unit in a multi-split system. With regard to liquid-refrigerant accumulation in a non-operating indoor unit, one possible case is that, during a heating operation, gaseous refrigerant enters the heat exchanger of the non-operating indoor unit and condenses there. However, because the gaseous refrigerant originally already contained a relatively large R1132(E) fraction within the cycle, even if it remains in the heat exchanger of the stopped indoor unit, it does not increase the R1132(E) composition ratio of the circulating refrigerant.

From the above considerations, the only location where the R1132(E) fraction in the circulating composition is highly likely to increase is the accumulator; therefore, the composition change in the accumulator is examined in A.5.2. Notably, this concept presupposes a system without configurations or controls, such as rectifiers, intended to deliberately control the refrigerant composition ratio.

A.5.2 Simplified calculation method for the maximum R1132(E) composition ratio

A specific method for calculating the maximum composition ratio of R1132(E) is presented below. First, the refrigeration cycle is assumed to be a simple cycle comprising a compressor, condenser, expansion valve, evaporator, and accumulator, as shown in Figure A.A.5-1(a). Liquid refrigerant is present in the accumulator and in the heat exchangers; however, because the liquid refrigerant inside the heat exchangers is flowing, it can be regarded as part of the circulating component, and composition change is unlikely to occur. In other words, from the standpoint of composition change, it is reasonable to treat all refrigerants other than the liquid refrigerant retained in the accumulator as gaseous refrigerants.

Accordingly, as shown in Figure A.A.5-1(b), the entire refrigeration cycle is regarded as a single vessel, and the gas-

phase component in that vessel is the component circulating through the refrigeration cycle. The liquid refrigerant discharged from the oil return hole of the accumulator is neglected in this analysis (even if this is neglected, the maximum R1132(E) composition ratio will not be underestimated).

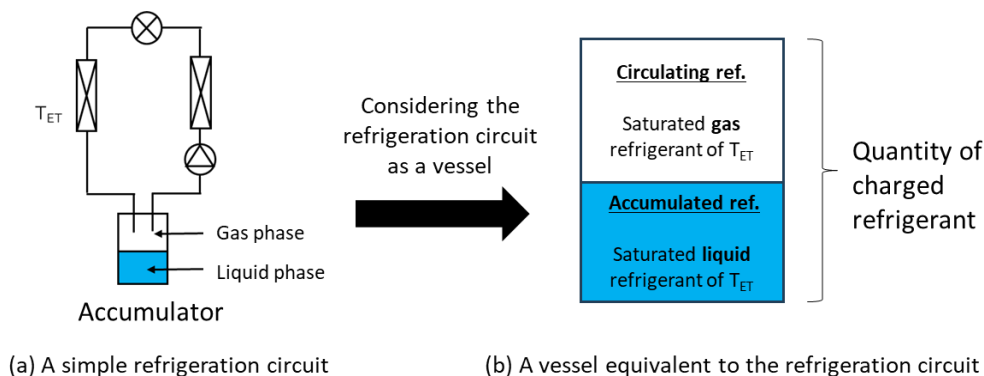


Figure A.A.5-1 Consideration of the refrigerant circuit to estimate the circulating composition

The refrigerant in the vessel separates into gas and liquid phases. The ratio of the amount of liquid refrigerant to the total refrigerant amount here is determined by the size of the vessel and the refrigerant amount (i.e., by the average refrigerant density in the vessel). The quality (x) at this time can be calculated using the following equation:

$$x = 1 - m_{Liq} / m_{Total}. \quad (A.5-1)$$

In this equation, the symbols represent the following:

x : Quality of the refrigerant in the vessel [-].

m_{Liq} : Amount of liquid refrigerant in the vessel [kg].

m_{Total} : Total refrigerant amount in the vessel [kg].

The composition ratios of the gas and liquid phases in the vessel can be obtained by refrigerant property calculations using the quality and temperature (required for refrigerant density calculations) as parameters (e.g., the “vapormassfraction” and “liquidmassfraction” functions of REFPROP provided by NIST).

In addition, the value of m_{Liq} / m_{Total} in Equation (A.5-1) reaches its maximum when the accumulator is filled with liquid refrigerant, at which point the composition ratio of R1132(E) in the gas phase becomes maximal. Here, the amount of liquid refrigerant accumulated in the accumulator is the physical maximum value of the accumulated liquid refrigerant amount, and the value of m_{Liq} / m_{Total} is defined as the “proportion of accumulated refrigerant.”

In this subsection, the actual calculation results for the maximum R1132(E) composition ratio are not discussed; however, the results obtained based on these calculations, as the ranges of equipment specifications considered capable of avoiding self-decomposition reactions, are described later in A.8.

A.6 Estimation of the self-decomposition reaction limit line and the R1132(E) limit composition ratio

Based on the results of the examination of the maximum input energy described above, refrigerant manufacturers estimated the self-decomposition reaction limit line at an input energy of 10 J and plotted it on a temperature–pressure map. In addition, the results of the reachable-condition verification for each self-decomposition reaction scenario were plotted on the same map. The results are shown in Figure A.A.6-1. In the figure, panel (a) addresses the two-component systems R474A and R474B, whereas panel (b) addresses the three-component system R479A.

A.6.1 Trend of the self-decomposition reaction limit line with respect to the R1132(E) composition ratio

Figure A.A.6-1 shows the self-decomposition reaction limit lines at 5% increments of the R1132(E) composition ratio. Solid lines are based on measured values, whereas dashed lines are estimates obtained by extrapolation. As the composition ratio of R1132(E) increases, the self-decomposition reaction limit line shifts toward a lower temperature and pressure. In particular, at an R1132(E) composition ratio of 55% for the two-component systems and 60% or more for the three-component system, the self-decomposition reaction limit line decreased to the range of normal operating conditions (120 °C and 4 MPa or less).

A.6.2 Trend of Reachable Scenario Conditions

The reachable scenario conditions were verified using R32, R410A, and R454C, and the maximum temperature and pressure values measured in the experiments were plotted directly. The numbers shown on the plots indicate the scenario numbers proposed within the WG. The reachable condition verification tests were conducted using refrigerants different from the target refrigerants because the existing refrigeration and air conditioning equipment primarily uses R32 and R410A, and the compressor and other component specifications, as well as the operating control and protection specifications, are optimized for those refrigerants. In addition, obtaining compatible target refrigerants and tuning equipment would require substantial time and effort. Furthermore, although the operating pressures of R32 and R410A are higher than those of the target refrigerants, it is safer to evaluate using refrigerants with higher pressures, considering that the R1132(E) composition ratio may increase owing to changes in the circulating composition, causing it to become a higher-pressure refrigerant. Accordingly, when plotting the temperature–pressure map, the pressures were kept at higher values without correcting them to the operating pressures of the target refrigerants.

The trends of the reachable scenario conditions can be divided into scenarios in which temperature increases markedly while pressure does not rise as much (hereinafter, “temperature-rise scenarios”) and scenarios in which pressure increases markedly while temperature does not rise as much (hereinafter, “pressure-rise scenarios”). Temperature-rise scenarios mainly occur under high-compression-ratio conditions or vacuum operation and when the compressor is energized in a state in which it is not compressing (idling or compressor lock). By contrast, pressure-rise scenarios mainly tend to occur owing to blockage of the high-pressure-side circuit (e.g., operation with a closed outdoor-unit gas-pipe valve (three-way valve)) or inhibited condensation in the condenser-side heat exchanger (e.g., stoppage of the condenser-side fan or blockage of the airflow path near the condenser).

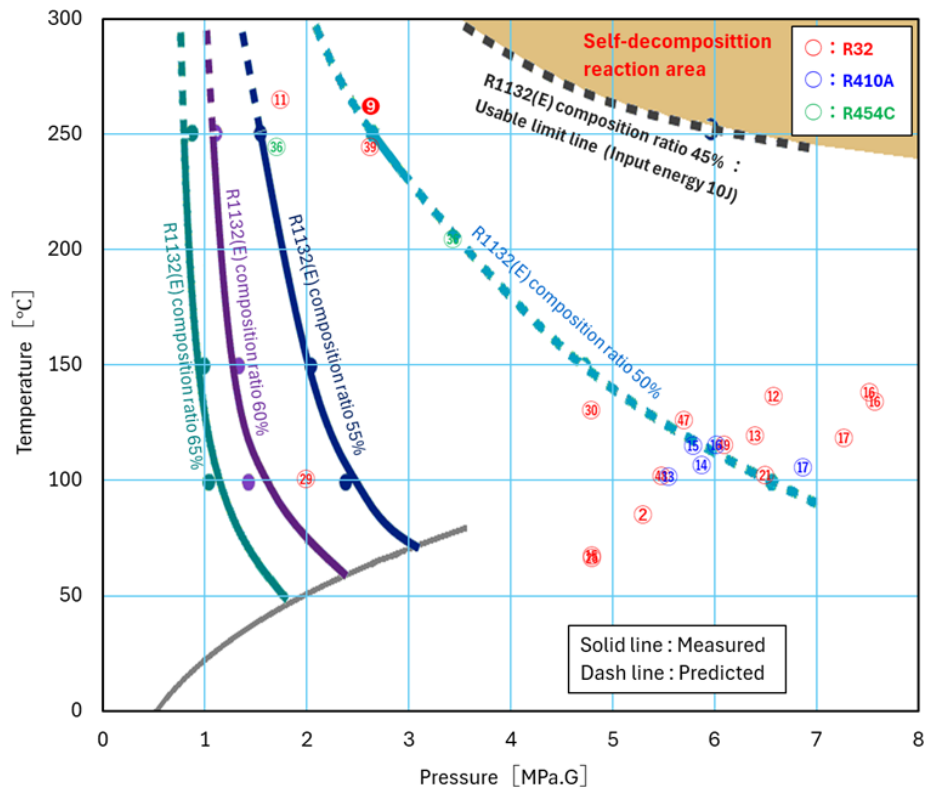
A.6.3 Setting the R1132(E) Limit Composition Ratio

In Figure A.A.6-1(a) and (b), the composition ratio of R1132(E), for which the self-decomposition reaction limit line is not exceeded at the reached temperature and pressure conditions of all scenarios confirmed to date, is defined as the “R1132(E) limit composition ratio.” In particular, the R1132(E) limit composition ratio is 45% for the two-component systems and 55% for the three-component system. These R1132(E) limit composition ratios correspond to an input energy of 10 J for inverter-driven equipment; if the input energy exceeds this value, the R1132(E) limit composition ratio would be lower.

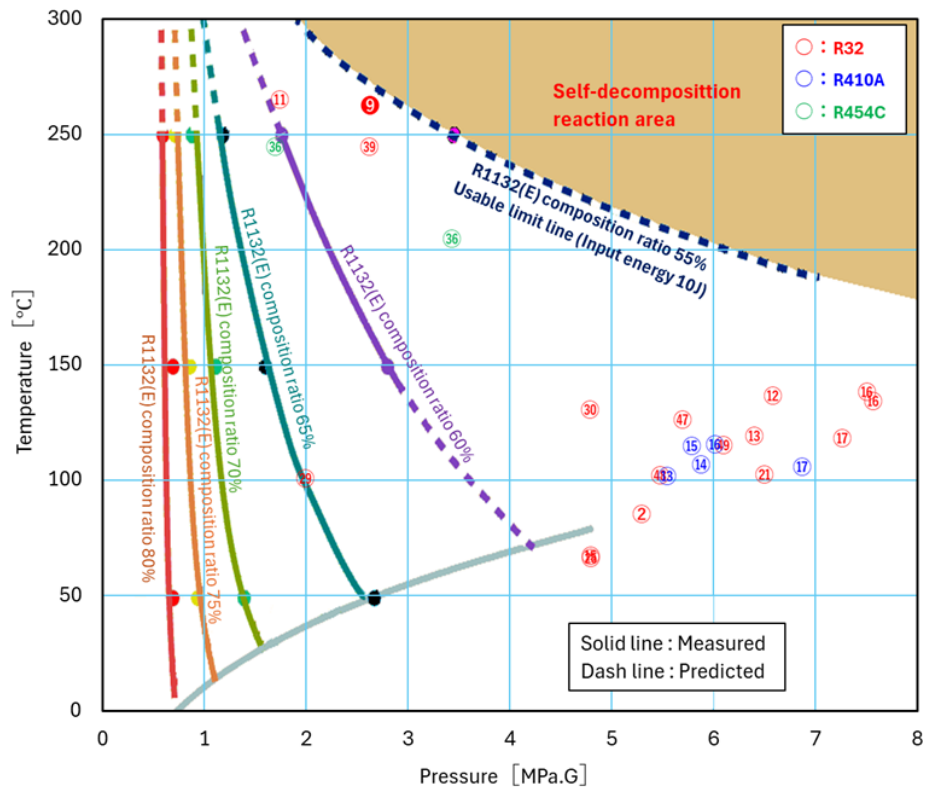
If the refrigerant is used within this R1132(E) limit composition ratio, the hazardous scenarios described above (i.e., scenarios that exceed the self-decomposition reaction limit line) do not exist. However, as discussed later in A.8, not all equipment specifications can satisfy the R1132(E) limit composition ratio. In such cases, examination, including an FTA for hazardous scenarios, becomes necessary.

At present, because Scenario No. 9 is the scenario closest to the self-decomposition reaction limit line, the description

of this scenario and the examination of its FTA are presented in A.7.



(a) Two-component systems (R474 series)



(b) Three-component system (R479 series)

Figure A.6-1 Self-decomposition limits and the reached temperature and pressure conditions of different scenarios.

A.7 FTA for Hazardous Scenarios

As described in A.6, Scenario No. 9 is currently the scenario closest to the self-decomposition reaction limit line; its description and the FTA for this scenario are presented below.

A.7.1 Results of the Reachable Condition Verification Test for Scenario No. 9

Scenario No. 9 is one of the temperature-rise scenarios and assumes that, for a domestic air conditioner, the refrigerant pump-down operation in the emergency operation mode is left unattended and the discharge temperature thermistor is displaced from its proper position so that the rise in compressor and discharge gas temperature cannot be detected. The equipment specifications and test conditions are outlined in Table A.7A.7-1.

Table A.7-1 Specifications of the apparatus and test conditions.

Items		Specifications / conditions
Specifications of the apparatus	Type of apparatus	Domestic air conditioner
	Capacity	2.2 kW
	Refrigerant	R32
	Power supply	1φ 100 V
	Compressor type	Rotary (rolling piston)
	Compressor shell type	High pressure
	Discharge temperature thermistor	Disabled (out of proper position)
Test conditions	Operation type	Pump down
	Operation mode of apparatus	Emergency operation mode (cooling)
	Ambient temperature	43 °C
	Procedure after pump down	Continue operating

The pump-down operation refers to the recovery of the refrigerant from the indoor unit to the outdoor unit during cooling operation. With the liquid-side valve (two-way valve) of the outdoor unit closed, the flow path by which the liquid refrigerant (two-phase refrigerant) is supplied from the outdoor unit to the indoor unit is blocked. As such, the refrigerant can flow from the indoor unit to the outdoor unit, but not in the reverse direction. Consequently, the refrigerant accumulates in the outdoor-unit heat exchanger (condenser). Once the transfer of refrigerant from the indoor unit to the outdoor unit is complete, the pump-down operation is typically terminated by closing the gas-side valve (three-way valve), thereby recovering the refrigerant in the refrigeration cycle into the outdoor unit. Scenario No. 9 corresponds to the case in which this operation is not terminated after pump-down is completed and the unit is left running.

The test revealed a sequence of changes over time. Initially, refrigerant on the indoor-unit side was recovered into the outdoor unit, causing the compressor suction pressure to decrease. Once recovery was completed, the system condition approached that of vacuum operation. Under normal conditions, the pump-down operation would have been terminated at this point. However, in the present scenario, the operation was intentionally continued, and the compressor remained under vacuum conditions. Because gas flow ceases under vacuum operation, the heat generated inside the compressor cylinder can no longer be removed, and the cylinder temperature rises. In addition, gas flow through the motor section

also ceases, preventing motor cooling and causing the motor temperature to increase owing to internal losses.

As the temperature inside the compressor cylinder rises, a component called the vane, which partitions the suction chamber and compression chamber, thermally expands and gets stuck between the upper and lower bearings so that it can no longer move. Consequently, the compressor can no longer compress and enters an idling state.

When the compressor shifts from compression operation to idling operation, the high-pressure-side temperature temporarily decreases slightly, after which it begins to rise again. The temperature increase occurs because no gas flows through the motor, and the heat generated by motor losses accumulates in the motor windings, causing the temperature to rise gradually.

The condition ultimately reached in this test was a compressor motor winding temperature of 262 °C. This temperature can melt the wire insulation, and although no short circuit was confirmed during the test, the motor wires could short-circuit and generate the input energy that serves as the initiation source of a self-decomposition reaction. The pressure condition inside the compressor was 2.62 MPa.G, corresponding to the saturation pressure of the refrigerant at the ambient temperature of the outdoor unit (43 °C).

Rare-earth magnets, which are widely used in current inverter compressors for air conditioning equipment, are vulnerable to heat and demagnetize when a certain amount of current flows through the motor at high temperatures. Therefore, we did not anticipate continued operation in the present test (i.e., that the inverter could continue to control the compressor) without substantial demagnetization even when the winding temperature reached 262 °C. However, we concluded that demagnetization did not occur because the compressor had entered an idling state, the load was light, and the amount of current was small. Incidentally, when a relatively large current flowed upon stopping the compressor at the end of the test, subsequent disassembly of the compressor revealed that the magnets had demagnetized to such an extent that operation was no longer possible.

A.7.2 FTA for Scenario No. 9

FTA was conducted for Scenario No. 9. The fault tree is shown in Figure A.A.7-1. The main factors affecting the occurrence probability of this scenario are the frequency with which pump-down is performed (for equipment servicing, relocation, and removal), the probability that the equipment is left in pump-down for an extended period (human error), the probability that protective devices fail to provide protection, and the probability of a high outdoor ambient temperature. The probability that protective devices fail to provide protection includes both the probability that the temperature cannot be detected and the probability that other protective functions do not operate. The “other protective functions” include, for example, an equipment function that stops operation after a certain period from the start of the pump-down mode. In the present study, such other protection was assumed to be absent (occurrence probability of 1.0).

The occurrence probabilities of the individual events require further scrutiny; therefore, specific values are not presented. However, the rough overall occurrence probability is approximately close to the target occurrence probability of 1.0×10^{-10} .

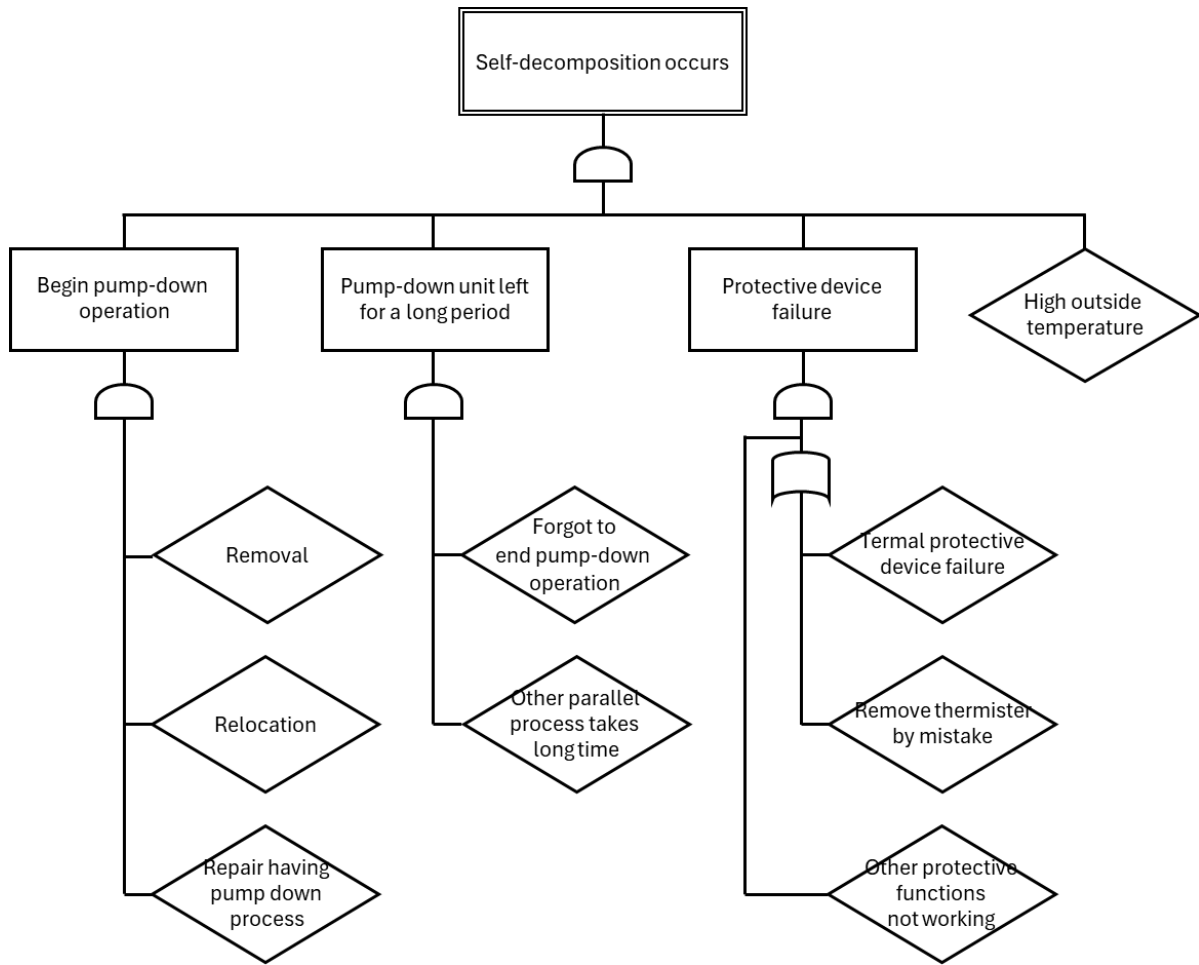


Figure A.7-1 Fault tree of scenario No. 9.

A.8 Equipment Specifications Currently Considered Capable of Avoiding Self-Decomposition Reactions

Based on the results in A.5 and A.6 above, the range of equipment specifications in inverter-driven equipment for which self-decomposition reactions are avoidable was examined. In particular, the assessment of whether self-decomposition reactions can be avoided was made using the accumulated refrigerant ratio defined in A.5 (the ratio of the maximum liquid refrigerant that can accumulate in the accumulator to the amount of refrigerant charge).

A.8.1 Calculation of the Proportion of Accumulated Refrigerant

The accumulated refrigerant ratio (P), which is the parameter required for judging whether self-decomposition reactions are avoidable, is obtained by the following equation:

$$P = V_a \rho / m, \quad (\text{A.8-1})$$

where

P : Proportion of accumulated refrigerant [-].

V_a : Effective internal volume of the accumulator [L].

ρ : Liquid refrigerant density [kg/L].
 m : Amount of refrigerant charge [kg].

Notably, the effective internal volume of the accumulator is the volume up to the height of the outlet tube, as shown in Figure A.A.8-1.

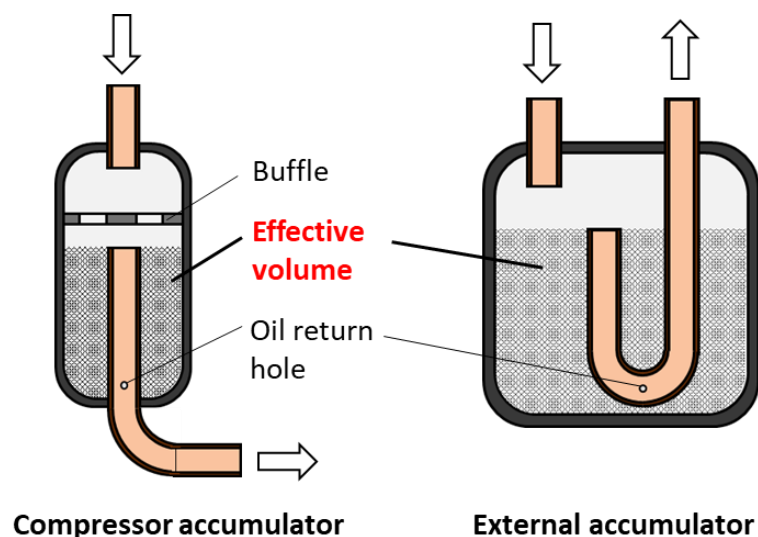


Figure A.8-1 Effective internal volume of the accumulator.

As the accumulated refrigerant ratio increases, the change in circulating composition becomes larger. In addition, because the density of the liquid refrigerant increases as the temperature decreases, the proportion of accumulated refrigerant also tends to increase. In the present examination, the minimum operable temperatures of the equipment were set to $-35\text{ }^{\circ}\text{C}$ and $-45\text{ }^{\circ}\text{C}$ for air conditioning and refrigeration equipment, respectively, and the circulating composition changes at those temperatures were examined to determine the conditions under which self-decomposition reactions are most likely to occur. The densities (ρ) of the respective refrigerants at the minimum operable temperatures were taken from Table A.8-1.

Table A.8-1 Liquid refrigerant density [ρ] at the minimum operating temperature.

Refrigerants	Air conditioners	Refrigeration equipment
R32	1.166 kg/L	1.194 kg/L
R410A	1.297 kg/L	1.329 kg/L
R404A	—	1.302 kg/L
Liquid temperature	$-35\text{ }^{\circ}\text{C}$	$-45\text{ }^{\circ}\text{C}$

Ideally, this calculation should use the values of the target refrigerants; however, because the properties of the target refrigerants are not currently publicly available, the values of conventional refrigerants were used as substitutes.

A.8.2 Judgment of Whether Self-Decomposition Reactions Are Avoidable

Table A.A.8-2 outlines the results of judging, for each target refrigerant, whether self-decomposition reactions are avoidable using the retained refrigerant ratio obtained in A.8.1. In the table, items marked with “✓” are considered

capable of avoiding self-decomposition reactions for all scenarios proposed to date. By contrast, items marked with “—” indicate that, at present, it cannot yet be established that self-decomposition reactions are avoidable for all scenarios.

Table A.8-2 Self-decomposition avoidance specifications.

Proportion of accumulated refrigerant	R474A	R474B	R479A
< 20 wt%	✓	✓	✓
20–40 wt%	✓	✓	✓
40–60 wt%	✓	—	✓
60–80 wt%	✓	—	✓
≥ 80 wt%	—	—	✓
Limit R1132(E) composition ratio	45 wt%	45 wt%	55 wt%
Initial R1132(E) composition ratio	23.0 wt%	31.5 wt%	28.0 wt%

✓: Self-decomposition reaction avoidable.

—: Not yet established as avoidable.

These judgment results were obtained by evaluating the parameters that impact the occurrence of self-decomposition reactions in the combinations most likely to lead to such reactions. As such, making a common judgment across various types of equipment is possible. Accordingly, the judgment is conservative with respect to the occurrence of self-decomposition reactions. In particular, the following state is assumed: maximum input energy (10 J), maximum liquid refrigerant density (the density at the minimum operable temperature), and maximum R1132(E) composition ratio (the accumulator retaining the maximum amount that can physically accumulate).

The judgment results suggest that self-decomposition reactions can be avoided for the three-component system R479A regardless of the proportion of accumulated refrigerant. By contrast, for the two-component systems R474A and R474B, equipment specifications remain for which avoidability cannot yet be established when the proportion of accumulated refrigerant is large. As noted above, the present assessment is intentionally conservative; therefore, self-decomposition reactions can be avoided for all scenarios through further refinement of the relevant parameters—particularly the input energy—and by setting equipment-specific parameters according to configuration, control strategy, and operating conditions. A more detailed assessment incorporating FTA-based scenario probabilities, as well as the magnitudes and joint probabilities of the various parameters affecting self-decomposition when those scenarios occur, may also demonstrate safe applicability.

A.9 Summary and future activities

From the results of the examination conducted by the JRAIA Self-Decomposition Reaction Risk Study WG, the following conclusions were obtained:

① For the single-phase 100 V inverter-driven unit of a 2.2 kW RAC, the input energy (discharge) generated when a short circuit occurred was less than 10 mJ for a phase-to-phase short circuit and less than 200 mJ for a ground fault. Considering application to inverters with different voltages or phase numbers and larger-capacity units with higher output, the maximum input energy for inverter-driven equipment was provisionally set to 10 J.

② At an input energy of 10 J, the R1132(E) limit composition ratio at which self-decomposition reactions can be avoided is 45 wt% for R474A and R474B and 55 wt% for R479A.

③ With respect to the composition change of refrigerants that may occur during equipment operation, a simplified method was established for calculating the maximum composition ratio of R1132(E) from the proportion of accumulated refrigerants.

④ In inverter-driven equipment, the proportion of accumulated refrigerant for which self-decomposition reactions are avoidable is 80 wt% or less for R474A and 40 wt% or less for R474B. Meanwhile, for R479A, self-decomposition reactions are avoidable irrespective of the proportion of accumulated refrigerant.

The results obtained through this examination were presented as follows:

① At the activity report meeting of the NEDO project “Development of High-Efficiency Refrigeration and Air-Conditioning Technologies for the Practical Use of Next-Generation Low-GWP Refrigerants” (held on 21 April 2025), this WG gave a presentation entitled “Refrigerant × Equipment Specifications Considered Capable of Avoiding Self-Decomposition Reactions.”

② At the International Symposium on Environment and New Refrigerants 2025 (23–24 October 2025), this WG gave a presentation entitled “Study on the Safe Use of Refrigerants with the Possibility of Self-Decomposition Reactions.”

Future issues to be examined and activities to be undertaken are as follows:

① For inverter-driven equipment other than single-phase 100 V units and for constant-speed equipment, the maximum input energy will be clarified experimentally, and the theoretical basis for the maximum input energy that can occur will also be examined.

② For equipment using R474A or R474B with a large proportion of accumulated refrigerant, and for which it could not be definitively stated in the present study that self-decomposition reactions are avoidable, the allowability of using these refrigerants will be judged through a detailed examination based on the refined results for the maximum input energy described above, refinement of the self-decomposition reaction limit, refinement of the R1132(E) composition ratio that may occur in scenarios that become hazardous as the R1132(E) composition ratio increases, and refinement of the scenario occurrence probabilities by FTA.

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