Basic Performance, Optimization, and Safety and Risk Evaluation of Next-Generation Refrigerants and Refrigerating and Air Conditioning Technologies

Part 2: Safety and Risk Evaluation of Next-Generation Refrigerants

Year 2020 Progress Report - Brief Edition -

June 1, 2021

Research Committee on Next-Generation Refrigerants,

Japan Society of Refrigerating and Air Conditioning Engineers (JSRAE)

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1. Introduction

1.1 Outline of the NEDO Project

No safety evaluation/risk evaluation methods have yet been established for strongly flammable refrigerant, such as hydrocarbons. Hence, it is important to understand the basic characteristics of next-generation refrigerants and, at the same time, to establish safety/risk evaluation methods for the challenges posed by next-generation refrigerants to work on the development of domestic safety standards as well as international standardization and standard development. It is also important to support the development of refrigerating and air-conditioning equipment that uses energy-saving and low global warming potential (GWP) next-generation refrigerants. Considering such circumstances, the New Energy and Industrial Technology Development Organization (NEDO) has established a development base for energy-saving refrigerating and air-conditioning equipment using next-generation refrigerants and has implemented a research and development project aimed at bringing refrigerants and refrigerating and air-conditioning equipment products to the market by 2026. One of the development themes is establishing safety/risk evaluation methods for next-generation refrigerants used for small- and medium-sized refrigerating and air-conditioning equipment, including commercial refrigerating equipment and residential air-conditioning equipment.

The NEDO Project, "Development of Next-Generation Refrigerating and Air Conditioning Technologies and Evaluation Methods for Achieving Energy-Saving and Low-Greenhouse Effects," includes, among others, a development theme titled "Development of safety/risk evaluation methods for next-generation refrigerants," which was jointly proposed by and commissioned to the University of Tokyo, Suwa University of Science, and the National Institute of Advanced Industrial Science and Technology (AIST) (Research Institute of Science for Safety and Sustainability). AIST (Research Institute for Sustainable Chemistry) has also received a NEDO-commissioned study that aims to evaluate the safety of low-GWP, low-flammability mixed refrigerants.

Product risk evaluation requires evaluating the occurrence frequency and severity of accidents. For a fire accident caused by flammable refrigerant leakage from refrigerating and air-conditioning equipment, three events, including rapid refrigerant leakage, the existence of a flammable space, and the existence of an ignition source, must coincide. The occurrence probability of a fire accident is the product of the probability of rapid refrigerant leakage multiplied by the existing flammable space probability and existing ignition source probability. Therefore, to determine the fire accident occurrence probability, the occurrence probabilities of these three factors must be determined.

In this project, we are researching the frequency of fire accident occurrences and research on accident severity evaluation. For the time being, selecting propane as the refrigerant, we focus on fire accidents associated with refrigerant leakage from room air conditioners and commercial reach-in display cabinets. The final risk assessment is underway in cooperation with the Japan Refrigeration and Air Conditioning Industry Association (JRAIA).

1.2 Activities of the WG II of the Research Committee for Next-Generation Refrigerants

The need for risk assessment of flammable refrigerants based on scientific knowledge is recognized to promote the use of flammable low-GWP refrigerants. A study on the safety of refrigerants is underway by the Suwa University of Science, the University of Tokyo, AIST, and other parties, as part of NEDO's project for the "Development of Next-Generation Refrigerating and Air Conditioning Technologies and Evaluation Methods for Achieving Energy-Saving and Low-Greenhouse Effects" (for the years 2018 to 2022). On the other hand, in 2016, JRAIA started to evaluate the risk arising from applying extremely flammable refrigerants (A3 refrigerants) to refrigerating and air-conditioning equipment. JRAIA separately discusses the effects of the installation conditions and the existence of ignition sources. To compile the knowledge from the above and perform objective evaluation from a third-person perspective, a "Research Committee on Next-Generation Refrigerants" was set up in 2018 as NEDO's investigation project inside the Japan Society of Refrigerating and Air Conditioning Engineers (JRAE). Deliberations on the safety of flammable refrigerants and their risk evaluation are in progress under the Investigation Committee's Working Group II (WG II).

2. Progress achieved at the University of Tokyo

The University of Tokyo received a commissioned study on the safety concerning the combustion of flammable refrigerants and risk evaluation. This study consisted of the following three themes: the risk due to flammable refrigerant leakage from a split air conditioner indoor unit, the risk due to its leakage from a commercial display cabinet, and the suppression of diesel explosions at the pump-down operation of split air conditioners.

For the first two study themes, the aim was to simulate the concentration diffusion of a flammable refrigerant as it leaks indoors from a room air conditioner or a commercial display cabinet and to calculate the change over time in the flammable gas volume. The obtained results enabled the calculation of the probability of ignition of the flammable refrigerant as it leaked indoors. This study first conducted leakage experiments using carbon dioxide and other safe, low-GWP gases and, then, used the obtained results to validate the simulation model.

A possible accident during the pump-down operation performed for refrigerant recovery from a heat pump is self-ignition combustion (diesel explosion), which occurs when air is mixed with a gaseous mixture of refrigerant and lubricating oil, and the temperature increases because of adiabatic compression. This study built an experimental setup that assumed diesel explosions to investigate the addition of a combustion-inhibiting substance to lubricating oil as a method of suppressing diesel explosions.

2.1 Refrigerant leakage from a residential split air-conditioner

Figure 2-1 shows an overview of the modeled room. The size was 3800 × 2400 × 2550 mm, and an air vent of 100 mm diameter and a gap under the door of dimensions 900 × 7 mm were provided facing the air conditioner. A mesh was set to appear finer near the boundaries. Based on IEC 60335-2-40:2018, the leak rate was set to discharge the total amount of refrigerant indoors within four min. R290 and R32 are the target refrigerants in the calculation.

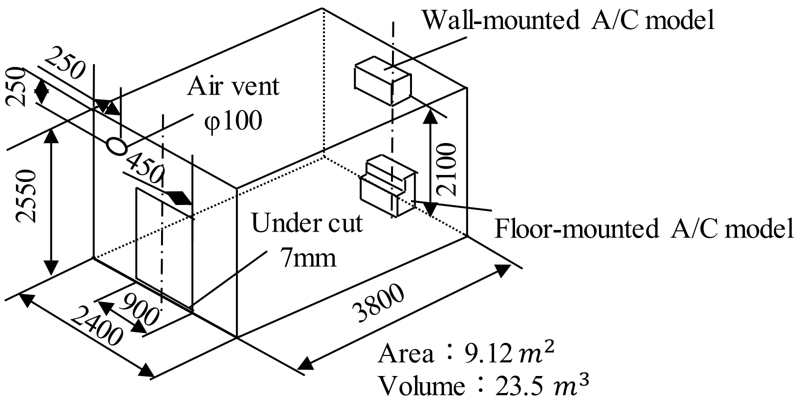


Fig. 2-1 Modeled room

To conduct a risk evaluation of indoor leakage of R290, one of the next-generation refrigerant candidates for residential air conditioners, the maximum allowable charge was evaluated by numerical fluid dynamics analysis. This study provides the following findings:

(1) The numerical fluid dynamics analysis method employed in this study was compared with refrigerant leakage experiments conducted using R744 and R32. The comparison showed that the concentration distributions of the refrigerants were highly reproducible, thereby validating the calculation method.

(2) Regarding the maximum allowable charge (Eq. (2-8) of the full version report), Eq. (2-8) was appropriate for wall-mounted air conditioners using R290 and R32. Regarding floor-mounted air conditioners, R32 was sufficiently safe, but R290 had an inadequate safety margin.

(3) Regarding the maximum allowable charge (Eq. (2-9) of the full version report), for wall-mounted air conditioners, the volume of flammable gas disappeared immediately after the fan operated or was generated directly under the outlet. Hence, the operation of the fan was very effective in reducing risk. For floor-mounted air conditioners,

flammable gas existed locally even after the fan was started, as long as the refrigerant continued to leak. However, the volume of the refrigerant flammable gas immediately disappeared at the end of the refrigerant leakage. This study revealed that an indoor unit fan that starts upon detecting leakage was necessary for assured safety and that a small volume of residual flammable gas remained in a large room even if the fan started operating 30 s after the onset of leakage.

2.2 Refrigerant leakage from a commercial display cabinet

The numerical calculation method was the same as the simulated leakage from a room air conditioner. Figure 2-2 shows an outline of the modeled room. The calculation model was sized equivalently to the laboratory built for the refrigerant leakage experiment described later. The size was 5600 × 3800 × 2550 mm, and a 100-mm diameter air vent in a wall adjacent to a modeled display cabinet was provided. This is because any shop installed with a display cabinet has an air vent. A mesh was set to appear finer near the boundaries. The initial indoor conditions were a gauge pressure of 0 Pa and a temperature of 300 K. For the inside of the display cabinet, the concentration of the refrigerant was appropriately determined from the refrigerant charge and the inside volume of the display cabinet. The pressure boundary conditions were set at the air vent.

Figure 2-3 shows the details of the modeled commercial display cabinet. The display cabinet was provided with two swing doors, and both were designed to open during the leak test. Above or below the display cabinet, a freezer was provided with a condenser fan designed to turn during the operation. Figure 2-3 shows a case with a freezer provided below the display cabinet. The display cabinet was allowed 100 mm from the wall surface to align the centerline of the display cabinet with that of the laboratory model. R290 was used as the refrigerant for the normal calculation. The swing doors were set to rotate at a rate of 60° per 3 s, as specified in the applicable international standards. The wind speed of the condenser fan, which had the effect of stirring the indoor air, was treated as a parameter.

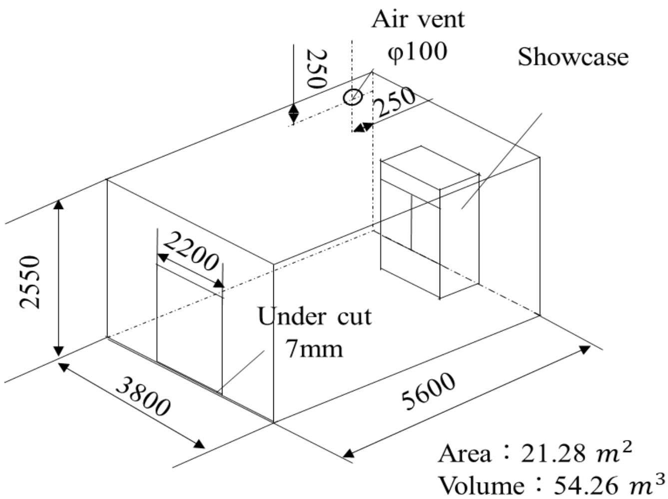


Fig. 2-2 Modeled room

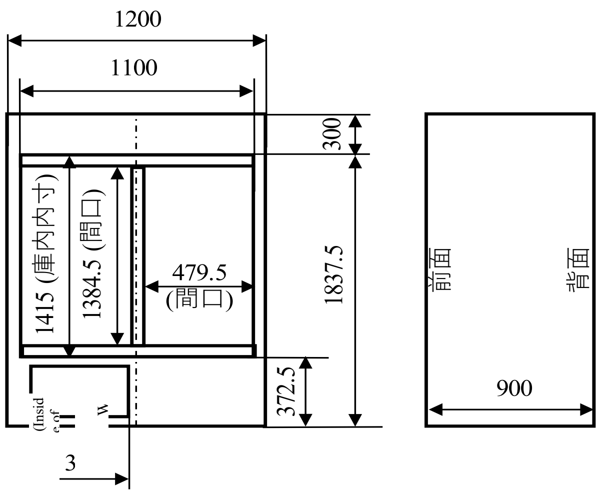


Fig. 2-3 Details of display cabinet

In the obsolete version of IEC 60335-2-89, the maximum refrigerant charge was specified as 150 g to ensure safety without activating any supplementary safety device. As a result of the 2019 revision, IEC 60335-2-89:2019 specified a formula for the maximum allowable refrigerant charge for flammable refrigerants, assuming that the condenser fan is operated during refrigerant leakage:

$$m_{max} = 13 \times LFL \qquad (2-1)$$

The lower flammable limit (LFL) of R290 is 0.038 kg/m^3; therefore, the maximum charge of R290 is 494 g. In this study, we evaluated Eq. (2-1).

For the purpose of risk assessment of indoor leakage of R290, one of the next-generation refrigerant candidates for commercial display cabinets, the effects of the refrigerant charge and fan operation on a flammable region generation scale were evaluated by numerical fluid dynamics analysis. This study provided the following findings:

1) To examine the validity of the numerical fluid dynamics analysis method employed in this study, a modeled display cabinet was provided in a room with a floor area of 21 m^2 to conduct refrigerant leakage experiments using R744. Assuming leakage into the display cabinet, the change over time in the indoor concentration distribution was measured with the door opened after the introduction and stirring of the refrigerant. This study examined the validity of the accuracy for approximately 5 min from leakage occurrence, which is expected to be important in risk evaluation, and subsequent accuracy.
2) The size of the flammable region was evaluated as the refrigerant charge increased without the condenser fan during operation. When 494 g of R290 was released, the combustible gas region remained for 30 min or more.
3) For each installation position, air velocity, and wind direction of the condenser fan, the changes in the volume of the flammable region and the time-integrated value were evaluated to investigate the effect of the stirring fan on decreasing the flammable gas region. For example, with the condenser fan installed below, the wind direction, whether forward or backward, made almost no difference on the effect of flammable gas dissipation.
4) With the condenser fan installed above, the effect of refrigerant gas stirring was almost invisible.

2.3 Suppression of diesel explosions at the pump-down of residential air conditioners

Air conditioner compressor explosion accidents occur in association with refrigerants. Reports on this type of accident are rare. In this type of accident, an air-conditioner compressor explodes when its internal pressure becomes abnormally high during the pump-down operation performed for refrigerant gas recovery into the outdoor unit before the relocation or disposal of the air conditioner. Considering that the inclusion of air is a necessary factor for a compressor explosion accident, we conducted experiments on the explosion of a mixture of air, refrigerant, and lubricating oil in a modeled engine simulating a compressor. We know that combustion occurs in a low refrigerant concentration region, causing increased pressure, and combustion requires lubricating oil. Our earlier studies have shown that oil (base oil) combustion propagates to the refrigerant, causing a further increase in pressure. The prevention of lubricating oil combustion can help reduce or prevent damage caused by compressor explosion accidents. Using polyol ester (POE) as the base oil and a phenol oxidation inhibitor (A1), an epoxy stabilizer (A2), and a phosphorus antiwear agent (P1) as additives, this study experimentally investigated how their concentrations and additive-refrigerant combinations affected the diesel explosion inhibition effect. The refrigerants used were R22, R32, R1234yf, and R290.

<u>With the phenol oxidation inhibitor (A1) added</u>

A comparison in terms of the upper-limit concentration of R22 refrigerant in its flammable range showed that the upper limit value decreased with the increase in additive concentration as follows: 32 vol% with no additive added; and 22 vol% and 5 vol% with additive A1 concentrations of 1 wt% and 5 wt%, respectively. These results revealed that an increase in the additive concentration significantly reduced the flammable range. The refrigerant concentration of R32 in its flammable range was from 0 to 20 vol%, which is narrower than R22's range of 0 to 30 vol% and wider than R1234yf's range of 0 to 6 vol%. In other words, refrigerants differed from each other in their flammable ranges. For R32 and R1234yf, the influence of the additive concentration was unclear but was observed to slightly reduce the flammable range. R290 had a narrow flammable range of 0 to 2.5 vol%.

<u>With the epoxy stabilizer (A2) added</u>

A comparison in terms of the upper-limit concentration of R22 refrigerant in its flammable range showed that the upper limit value decreased, albeit not significantly, with the increase in additive concentration as follows: 32 vol% with no additive added; and 22 vol% and 18 vol% with additive A2 concentration of 1 wt% and 5 wt%, respectively. Another comparison in terms of the upper-limit concentration of R32 refrigerant in its flammable range showed that the upper-limit value changed as follows: 20 vol% with no additive added, 10 vol% with an additive concentration of 1 wt%, and the disappearance of the flammable range with an additive concentration of 5 wt%. The upper-limit concentration of the R1234yf refrigerant in its flammable range did not show a particularly systematic tendency. For R290, the flammable range disappeared even at an additive concentration of 1%.

<u>With the addition of the phosphorus antiwear agent (P1)</u>

The influence of the concentration of the additive P1 on the combustion of the refrigerant showed a similar tendency to that of additive A1. A comparison in terms of the upper-limit concentration of R22 refrigerant in its flammable range for each additive concentration showed that the value was 32 vol% with no additive added, and 25 vol% and 20 vol% with additive P1 concentrations of 1 wt% and 5 wt%, respectively. Thus, the upper-limit value and the non-dimensional maximum pressure decreased with an increase in additive concentration. However, the combustion and pressure-inhibiting effects of additive P1 were smaller than those of additive A1. The additive provided R32 and R290 with combustion and pressure-inhibiting effects, similar to those provided by additive A1.

Summary

The experimental results provided the following findings:

1) Additives affect the flammable range and the maximum pressure. As the additive concentration increased, the flammable range became narrower, and the maximum pressure decreased. Therefore, an increased additive concentration, which increased the combustion-inhibiting effect and reduced the destructive force of explosions, was expected to reduce the occurrence probability of refrigerant compressor explosion accidents and the scale of the resulting damage.
2) The combustion-inhibiting effect varied depending on the combination of the refrigerant and the additive. Additive A2 showed an inhibitory effect on many refrigerants, even when added at a concentration of 1%. For R290 and R1234yf in particular, the concentration range for the occurrence of diesel explosions was significantly reduced.
3) R290 showed an extremely narrow range for the occurrence of diesel explosions compared with the other refrigerants.

3. Progress achieved at Suwa University of Science

We conducted a research and development project with the aim of developing an evaluation method for devices and phenomena that may become a potential ignition source during the use of residential air-conditioning equipment and commercial reach-in display cabinets charged with next-generation refrigerants. More specifically, through bibliographic and web surveys, experiments, numerical simulations, and other methods, we evaluated the possibility that the R290 (propane)-air mixture leaked and accumulated from the above equipment ignites due to sparks produced from the operation of contact relays, contact switches, or similar devices or other causes, including cigarettes and hot surfaces.

We selected ignition sources based on a close connection with the results of risk assessment performed by the JRAIA for residential air-conditioning appliances and commercial refrigerating equipment.

3.1 Extraction of ignition sources and an evaluation method for their ignition capability

Ignition sources, which must be studied in detail because of their ignition risk, as pointed out by the JRAIA during the risk assessment regarding the introduction of propane into residential air-conditioning appliances and commercial refrigerating equipment, were classified into the large categories of electrical sparks, high-temperature hot surfaces, and open flames. The ignition mechanism was studied for each of these categories. Next, we classified the large categories of electrical devices and phenomena likely to be potential ignition sources and decided to evaluate them in terms of ignition possibility based on the ignition mechanism model for each large category.

3.2 Ignition possibility evaluation of various ignition sources

3.2.1 Evaluation of ignition possibility of electrical sparks

For this sub-theme, we experimentally studied (1) the ignition possibility due to arc discharges from contact relays, (2) the ignition possibility due to the operation of wall-mounted switches for lighting, and (3) the ignition possibility due to arc discharges caused by plugging and unplugging of general home electrical appliances. In addition, we evaluated the ignition possibility due to static electricity based mainly on bibliographic and web surveys. The results thus obtained include the following:

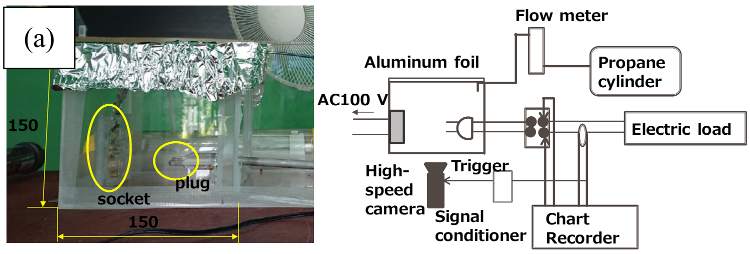
(1) Based on the idea that ignition depends on the balance between the heat generation rate and heat release rate, we devised a method to easily evaluate the ignitability by comparing the discharge energy generated within a specific time with the minimum ignition energy. We used this method to screen general home appliance products in terms of ignition possibility.

(2) Regarding the ignition possibility due to arc discharges from contact relays, we experimentally showed that the electrical discharge energy increases depending on the power consumption, that the switch closing movement causes a larger electrical discharge energy than the switch opening movement, and that the electrical discharge energy exceeds the minimum ignition energy for propane-air mixtures. In addition to demonstrating that the circuit's current size affects that of the electrical discharge energy, we presented the possibility that the circuit's current value may serve as an indicator for predicting the ignition frequency.

(3) We experimented on propane-air mixture ignition due to the operation of a wall-mounted switch for lighting. We observed the possibility that the flammable gaseous mixture could flow into the contact casing. Moreover, the electrical discharge energy at contact may exceed the minimum ignition energy. Hence, as per our expectation, the ignition possibility was undeniable. In the experiment, however, we did not observe a single occurrence of ignition. The likely cause was that the contact-to-contact distance was too small for a flame to become sufficiently large for steady propagation.

(4) A hairdryer was observed to be ignited upon plugging while plugging and unplugging in a propane-air pre-mixed gas in the experiment. The probability of ignition showed a tendency to increase with the increase in power consumption (Fig. 3-1). Besides, a case was observed in which a product compliant with an overseas standard (230 VAC) was similarly ignited in a propane-air pre-mixed gas. In both cases, an electrical discharge energy greater than the minimum ignition energy by 2 to 3 digits was measured.

(5) For the ignition risk due to electrostatic discharge, we studied scenarios and compared the ignition risk due to known discharge characteristics. It was found that the possibility of ignition due to a discharge from the contact between an electrically charged human body and a doorknob is undeniable, whereas the ignition possibility due to static electricity caused by undressing is negligible.



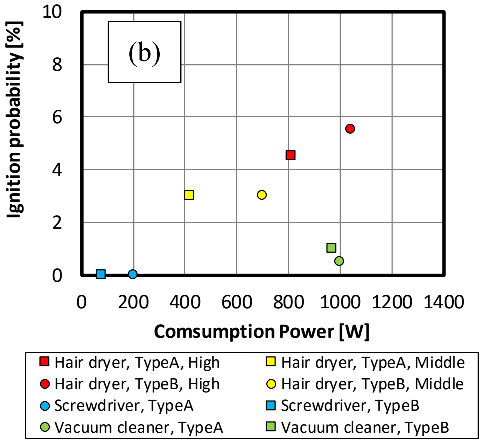


Fig.3-1 Experimental evaluation of ignition possibility of R290/air mixture by plugging/unplugging the power plug of general appliances.
(a) Photo and schematic diagram of the experimental setup
(b) Dependence of ignition possibility on consumption power

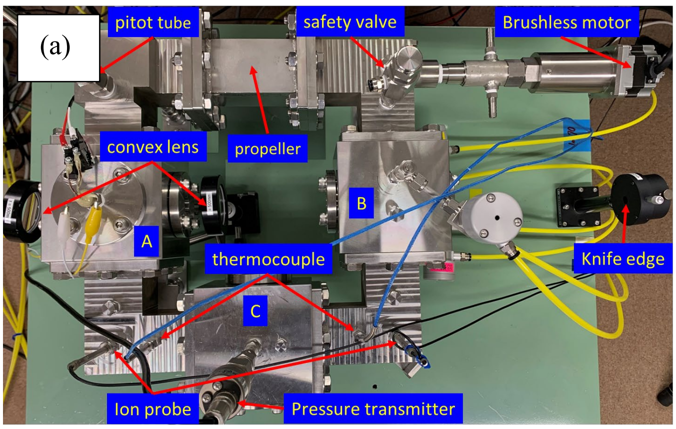
3.2.2 Evaluation of ignition possibility due to high-temperature surfaces

For this sub-theme, we experimentally evaluated the ignition possibility due to high-temperature hot surfaces represented by cigarettes. First, a model experiment was conducted to clarify the critical condition for ignition due to the hot surface of an R290-air gaseous mixture. Then, the concentration of R290, the flow rate, the dimensions of the hot surface, and the supply power to the hot surface were changed as experimental parameters. The findings thus obtained mainly include the following:

(1) A clear correlation exists between the supply power and ignition time. The influence of concentration on this correlation was small. In addition, the ignition time became infinite (i.e., non-ignition) at a certain level of supply power, which means that a critical ignition heat flux governing the ignition or no-ignition existed and its value increased with the increase in flow rate (in other words, reduced flammability) (Fig.3-2). While this tendency was not affected by the heater’s dimensions, the critical ignition heat flux was significantly intensified when the heater was small.

(2) By expressing the non-dimensional critical heat flux $q_{w\_c}^{*}$ as a function of the Damköhler number, we found that the critical ignition heat flux can be predicted for various heater dimensions.

(3) Considering the critical ignition heat flux values obtained through the model experiment and theoretical analysis and the dependence on the heater size, the ignition possibility of hot surfaces such as cigarettes was probably extremely minimal.



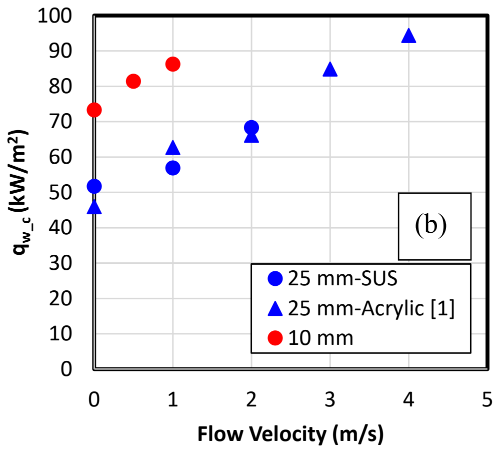


Fig. 3-2 Experimental investigation of ignition possibility of R290/air mixture by a heated surface.
(a) Photo of the experimental setup (b) Dependence of the critical heat flux for ignition on the flow velocity

4. Progress achieved at the Research Institute of Science for Safety and Sustainability, AIST

The Research Institute of Science for Safety and Sustainability at the National Institute of AIST has been in charge of the following two research themes: ignition capability evaluation for investigating whether home appliances and other devices present indoors can become an ignition source when a flammable concentration region is formed owing to the indoor leakage of a flammable refrigerant, and full-scale physical hazard evaluation of a possible leak fire accident involving a room air conditioner indoor unit or a refrigerated reach-in display cabinet.

4.1 Ignitability evaluation of real devices present in flammable concentration regions

To obtain the basic data for determining the risk assessment probability of ignition caused by the occurrence of accidental refrigerant leakage from devices charged with propane (R290), a flammable gas, regarded as one of the next-generation refrigerant candidates with a low GWP, we repeatedly remote-controlled electrical equipment in a container filled with approximately 5.2% propane-air pre-mixed gas, which is regarded as the most prone to electrostatic ignition, to observe whether ignition occurred.

4.1.1 Appliances selected for evaluation and experimental method

So far, we have conducted ignition evaluation experiments using a laser printer, a hair dryer, an electric vacuum cleaner, an electric screwdriver, an electric cooking hot plate, and a kerosene fan heater.

For the ignitability evaluation experiments, except for that of the kerosene fan heater, we used a 1.00 × 1.00 × 1.00 m acrylic container consisting of four acrylic side walls, a steel floor, and a plastic sheet stretched over the ceiling. The acrylic container was installed in an explosion pit at the AIST. After placing the appliances fitted with an air actuator for remote control in the container, we introduced propane and air into the container while adjusting their flow rates. With the propane concentration adjusted and maintained at approximately 5.2% by a concentration sensor, the appliances were awitched on and off hundreds of times by remote control from outside the explosion pit. A high-speed infrared camera and a normal-speed visible-range camera were used to observe the ignitions.

4.1.2 Results of ignitability evaluation experiments

The hair dryer, electric vacuum cleaner, electric cooking hot plate, and kerosene fan heater were used to catch fire. Although the experimental results were obtained using a single model, we considered that the risk assessment of the probability of ignition due to operation in a flammable concentration region should be unity. If there is a possibility that ignition will not occur according to differences in power consumption or structure, we will conduct additional tests.

The laser printer and electric drill were not observed to catch fire. Because the evaluation is based on a single model and a limited number of repeated experiments, the ignition probability of these appliances that do not have an explosion-proof structure cannot be set to zero in the risk assessment. In the future, if the number of models and the number of repeated experiments are added, and it is confirmed that ignition does not occur, the ignition probability in risk assessment can be reduced according to the number of repeated experiments.

a) b) c) d)

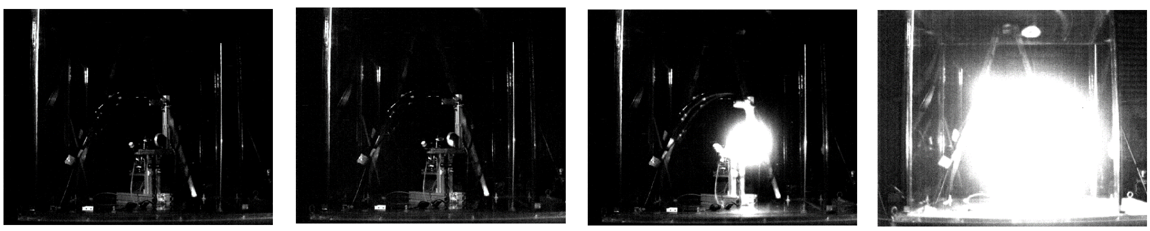


Fig. 4-1 Images taken by near infrared high-speed video camera

4.2 Diffusion behavior measurement and physical hazard evaluation of room air-conditioner indoor unit

To determine the risk assessment severity of accidental leakage from a room air conditioner indoor unit using propane (R290) as the refrigerant, we evaluated the combustion effects of a leak fire accident. This combustion effect evaluation assumes real use conditions. Hence, we installed a room air conditioner indoor unit in a full-scale simulated room, measured the leakage and diffusion behaviors under several probable leakage conditions, and conducted ignition experiments for conditions expected to result in a high severity. Consequently, we evaluated the effects of the combustion.

4.2.1 Measurement of leakage and diffusion behaviors for the room air conditioner indoor unit

We set up a 2.7 × 5.4 × 2.4 m wooden simulated room in a large indoor space at the Detonation Tube Laboratory of the National Institute of Occupational Safety and Health, Japan. We added an indoor partition wall to measure in another space measuring 2.7 × 2.7 × 2.4 m. At the center of the short side of the 2.7 × 5.4 m space, we installed the indoor unit of a split-type room air conditioner with its bottom part positioned at the level 2.00 m from the floor surface.

The full amount of propane was discharged evenly in 4 min. We used the maximum allowable charge determined by Kataoka's formula adopted in IEC60335-2-40:2018 for rooms without air agitation and other safety measures, as well as the allowable charge relaxed based on the premise of air agitation.

After the completion of any of the experiments that discharged the maximum allowable charge volume calculated using Kataoka's formula, no flammable concentration region of propane was observed. In addition, with air distribution in operation during all the experiments that stirred indoor air using the air distribution function of the air conditioner, no flammable concentration region was observed. In other words, the flammable concentration region was observed after the end of the discharge only when the relaxed refrigerant charge on the premise of ventilation was released without ventilation.

4.2.2 Full-scale physical hazard evaluation of the room air conditioner indoor unit

In the outdoor laboratory at the site of the now-defunct Hitachi Cement Taiheida Mine Accumulation Grounds, a 2.7 × 5.4 × 2.4 m steel-made simulated room was set up to conduct a combustion effect assessment experiment by discharging and igniting propane in the same way as that used for the diffusion behavior measurement. To observe the combustion effects under conditions close to the real room, a 180 cm wide, double-sliding glass-paned sweep window was provided at the center of the wall opposite to the short side wall of the 2.7 × 5.4 m space mounted with the room air conditioner indoor unit. For ignition, we used electrical sparks discharged by raising the AC voltage of 100 V from the power generator to 15 kV via a neon-sign transformer.

No fire broke out even with ignition immediately after the refrigerant charge of 330 g calculated by Kataoka's formula was fully discharged in 4 min without the indoor unit fan being operated, 2 cm above the floor at the center of the simulated room. In addition, no fire broke out even with ignition 2 cm above the center of the floor of the simulated room immediately after the relaxed charge of 625 g was fully discharged in 4 min with the indoor unit fan blowing horizontally in continuous weak operation.

The refrigerant charge of 330 g, calculated using Kataoka's formula, was discharged at the rate of full volume discharge in 4 min without the indoor unit fan in operation. During the discharge, more specifically, at 3 min and 30 s after the start of discharge, we observed that a fire broke out with ignition 150 cm above the floor below the indoor, resulting in a completely burned air conditioner indoor unit. The maximum value of the measured internal pressure was 2.3 kPa, while that of radiant heat was 7.5 kW m^{-2}. Figure 4-2 shows the still images taken at intervals of 200 ms immediately after the fire occurred.

a) b) c) d)

Fig. 4-2 Fire observed after ignition at 30 s before finishing blowout. (200 ms each)

Moreover, we observed that the fire broke out with ignition 2 cm above the center of the floor of the simulated room immediately after the relaxed charge of 625 g was fully discharged in 4 min without operation of the indoor unit fan. The glass-paned sweep window in front of the indoor unit was damaged both on the sash and the panes and blown outdoors in pieces. The maximum value of the measured internal pressure was 5.6 kPa, whereas that of radiant heat was 6.1 kW m^{-2}. The maximum value of the blast pressure measured 10 m outside the sweep window was 36 Pa. If the increase in internal pressure is limited because of a damaged glass-paned window, combustion will not significantly affect the human body.

4.3 Diffusion behavior measurement and physical hazard evaluation of reach-in display cabinet

To determine the risk assessment severity of accidental leakage from a reach-in refrigerated display cabinet using propane (R290) as the refrigerant, we evaluated the combustion effects of leak fire accidents. This combustion effect evaluation assumes real use conditions. Hence, we installed a reach-in display cabinet in a full-scale simulated room, measured the leakage and diffusion behaviors under several probable leak conditions, and conducted ignition experiments for conditions expected to result in a high severity in the event that a fire breaks out to evaluate the combustion effects.

4.3.1 Measurement of leakage and diffusion behaviors in the reach-in refrigerated display cabinet

We set up a 4.9 × 4.9 × 2.8 m wooden simulated room in a large indoor space for the measurement. A refrigerated display cabinet measuring 120 cm wide, 85 cm deep, and approximately 200 cm high was installed at the center of one of the walls of the simulated room. The reach-in display cabinet was a double-doored type, with the compressor and other mechanical components provided in the lower part of the display cabinet.

The propane was leaked, assuming that the full amount of propane charged as the refrigerant first leaks and spreads into the display cabinet and that the doors are opened when an even concentration of propane is held in its full amount inside the cabinet. Three refrigerant charges were selected: 100 g, 500 g, and 1000 g. Both doors of the double-doored display cabinet were opened simultaneously for 3 s up to an angle of 60°by remotely operating the air actuators fitted on the doors from the measurement room outside of the large experimental space.

The standard condition was to operate the condenser fan at the bottom of the display cabinet with a refrigerant charge of 500 g, which is considered for relaxation on the premise of forced agitation of indoor air. The refrigerant diffusion behavior was measured while changing the conditions such as the refrigerant charge, the presence/absence of fan operation, and the presence/absence of refrigerated products in the cabinet. When the condenser fan was operated, 500 g of refrigerant charge leaked into the cabinet, and approximately 5 min after the doors were opened, the combustible concentration region in the simulated room disappeared. When a refrigerant charge of 500 g leaked into the cabinet and the doors were opened without operating the condenser fan, a flammable concentration region continued to form in the simulated room for 90 min. Even when the condenser fan was not operated, the flammable concentration region disappeared within 1 min when the refrigerant charge was 100 g. The effect of the simulated refrigerated bottle placed in the cabinet was not significant.

4.3.2 Full-scale physical hazard evaluation of the reach-in refrigerated display cabinet

A 4.9 × 4.9 × 2.8 m steel-made simulated room was set up in the outdoor laboratory to conduct combustion effect assessment experiments by discharging and igniting the propane in the same way as with diffusion behavior measurement. To observe combustion effects under conditions close to a real room, a 240-cm wide, double-sliding glass-paned door simulating an automated door was installed on the wall opposite to the wall mounted with the display cabinet.

The propane leaked into the cabinet while the condenser fan at the bottom of the refrigerating chamber of the reach-in display cabinet of the same type used for measuring the leakage and diffusion behavior was operating. The propane concentration in the cabinet was 26% when the refrigerant charge of 500 g leaked. We measured the refrigerant concentration in the cabinet. When the refrigerant concentration reached a predetermined value, the doors were opened by remote control, and a discharge spark was provided as ignition. Combustion did not occur when ignited at 2 cm above the floor in the center of the room and 5 min after the showcase door was opened. When ignited at 50 cm in front of the showcase door, 2 cm above the floor, and 40 s after the showcase door was opened, combustion was confirmed, but the simulated room glass door was not damaged. Immediately after the showcase door was opened, when it was ignited at 50 cm in front of the showcase door and 2 cm above the floor, combustion was confirmed, and both the window frame and glass of the simulated room glass window were damaged and scattered. Figure 4-3 shows the still images of indoor flame propagation taken every 100 ms immediately after the fire broke out. The glass-paned door was blown outward because of the increased internal pressure of the simulated room, and damage to its panes was observed.

The maximum value of the measured internal pressure increase was 5.0 kPa, and the maximum blast pressure at 10 m outside the sweep window was 29 Pa. The increase in internal pressure was limited to approximately 5 kPa because of damage to the glass-paned window. The blast pressure caused no significant effects outdoors.

The maximum value of the measured radiant heat was approximately 160 kW m^{-2}, both indoors and outdoors. Although short in duration, the radiant heat had a severity that was so intense, it caused burn injury.

a) b) c) d)

Fig. 4-3 Fire observed after opening the door with continuous ignitions. (100 ms each)

In addition, assuming that 100 g of propane leaked into the display cabinet during the operation of the condenser fan at the bottom of the refrigerated compartment, we adjusted the propane concentration inside the display cabinet to 5.2% and remotely opened the doors so that discharge sparks caused ignition at 2 cm above the floor and 50 cm in front of the display cabinet door. We observed fire and damage on the frame of the glass-paned door of the simulated room without scattering of glass shards. The maximum value of the internal pressure was 4.4 kPa, and the maximum value of the radiant heat was 8.7 kW m^{-2}. The maximum value of the blast pressure measured 10 m outside the sweep window was 26 Pa.

5. Progress achieved at the Research Institute for Sustainable Chemistry, AIST

This research and development has the particular purpose of clarifying the effect of mixing of fluorine refrigerants on the safety (flammability) characteristics, etc. to support the development and dissemination of refrigerants with low GWP and excellent safety. Assuming the combination of flammable low GWP refrigerant and low-flammability refrigerant as the evaluation target, we will clarify the mixing composition range with high safety equivalent or more to gas satisfying the safety standard of refrigerants that are examined domestically and overseas (e.g., gas classified into "Lower flammability class" (Class 2 L) in International Standard ISO817 and positioned as "Specific inert gas" in the High Pressure Gas Safety Act). In addition, considering the future commercialization of low-GWP refrigerants, we will evaluate the effects of temperature, humidity, and concentration distribution of refrigerants on flammability.

From FY 2018–2020, we selected an R32/1234yf mixture as a target of a new low-GWP blend refrigerant, evaluated the flammability characteristics of each mixing composition of the refrigerant mixture, such as the flammability limits, burning velocity, and quenching distance, under standard conditions and various temperature and humidity conditions, and accumulated the data. As a result, we clarified that the new low-GWP refrigerant mixture exhibits flammability characteristics that are lower than those of the existing "Specific inert gas" (R1234yf and R32) under practical temperature and humidity conditions in an arbitrary mixing composition.

5.1 Evaluation of flammability limit of low GWP refrigerant mixture

To evaluate the flammability limits, we conducted measurements using the EN1839B method, which shows the results closest to the flammability limits of real scale for various refrigerants and is implemented in the method that judges based on the pressure rise rate $100\times(P_{max} - P_0)/P_0 \geq 30$ (%). The results of independent measurements under dry conditions at 25°C for gases R32 and R1234yf, which are constituents of many blend refrigerants, are shown in Fig. 5-1. When judging with the pressure rise rate of 30%, the flammability limit (lower limit, LFL) was 13.7 vol% for R32 and 6.8 vol% for R1234yf. To clarify the effect of the flammability limit on temperature and humidity for simple substances of R32 and R1234yf, we first measured the effect of temperature. As a result, we found that the flammability limits did not significantly change in the practical temperature range of 15-60°C. Furthermore, we measured the effect of humidity on the flammability limits of simple substances of R32 and R1234yf. We functionalized the flammability limits against the relative humidity.

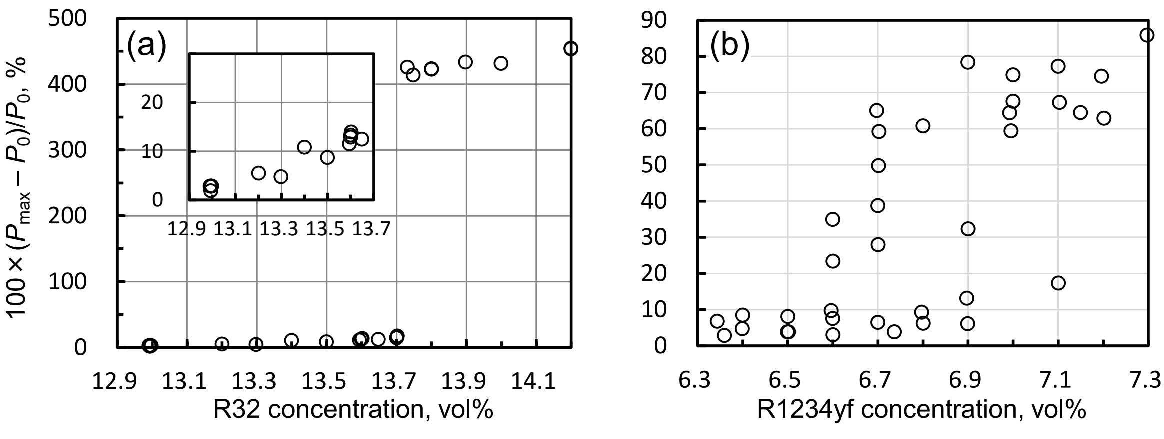


Fig. 5-1 Pressure rise rate vs. refrigerant concentration measured by the EN1839 B method for (a) R32 and (b) R1234yf at 25°C and 0% RH.

Next, we measured the temperature dependence of the flammability limits against the mixing ratio for the R32/1234yf blend (temperature range of 15-60°C and humidity of 0%RH). We recognized that no significant change in the flammability limits was found to be similar to every single substance in this temperature range. We found that the flammability limit in dry air increased monotonously as the molar mixing ratio of R32 increased for both the upper limit (UFL) and the lower limit (LFL), which was almost in accordance with Le Chatlier's formula, and it could be approximated by a simple quadratic equation.

Moreover, we investigated the effect of humidity on the flammability limits of the R32/1234yf blend. The measurement temperature was maintained at 35°C, and the highest relative humidity was 63%RH in conversion to 35°C for both the LFL and UFL. The results are shown in Fig. 5-2. In any case, it was found that the flammability limit value (y) could be well approximated by a quadratic equation in the form of $y = \mathrm{a}x^2 + \mathrm{b}x + \mathrm{c}$ for the R32 mol mixing ratio (x). Quadrant equations for the relative humidity (r = %RH/100) were obtained by applying the least-squares method to the values of coefficients a, b, and c, depending on the mixing ratio obtained for each of the LFL and UFL. If, for example, $r = 0.50$ is substituted for the equation thus obtained, the predictive values of LFL and UFL for the arbitrary mixing composition at a relative humidity of 50%RH are obtained. As a result of the actual verification, the predictive values coincided with the measured values within the error range. It was shown that this blend has the possibility that the flammability limits can be predicted in the arbitrary mixing ratio and humidity, as well as within the practical temperature range.

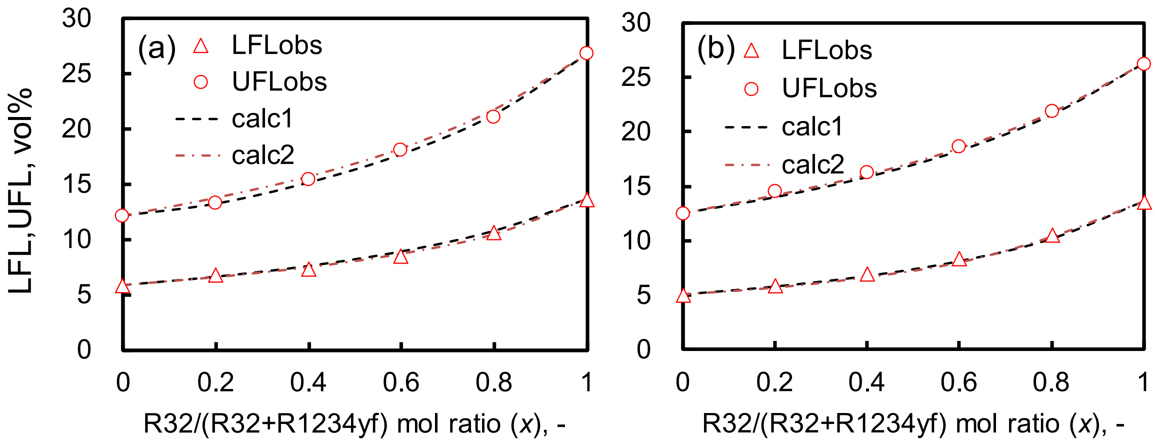


Fig. 5-2 Effect of humidity on flammability limits of R32/1234yf mixtures measured at (a) 35°C and 10%RH and (b) 35°C and 63%RH.

5.2 Evaluation of burning velocity of low GWP refrigerant mixture

We evaluated the mixing ratio dependence of the burning velocity under various temperature and humidity conditions for the R32/1234yf mixture using the Schlieren visualization method. First, we performed measurements over a wide range of temperatures for the entire range of mixing ratios at a humidity of 0%RH. Figure 5-3 shows an example of these results. We found that the difference in the maximum burning velocity ($S_{u,max}$) is rarely observed within the practical temperature range, similar to the case of the flammability limits. In addition, the burning velocity monotonously increased as the R32 mol mixing ratio increased in the dry air condition, and a significant increase in the burning velocity was not observed until the R32 mixing ratio exceeded approximately 0.5, similar to the tendency of the flame temperature. As shown by the curve in Fig. 5-3, the maximum burning velocity of this mixture can be well expressed by the mass fraction- or energy fraction-based Le Chatelier's formula. In addition, we performed an evaluation of the effect of humidity on the burning velocity at 35°C for this mixture. In conclusion, it was found that this mixture showed a maximum burning velocity lower than that of single R1234yf and R32 under the same conditions within the practical temperature and humidity conditions at 35°C or less and 63%RH or less, respectively, in the arbitrary mixing composition.

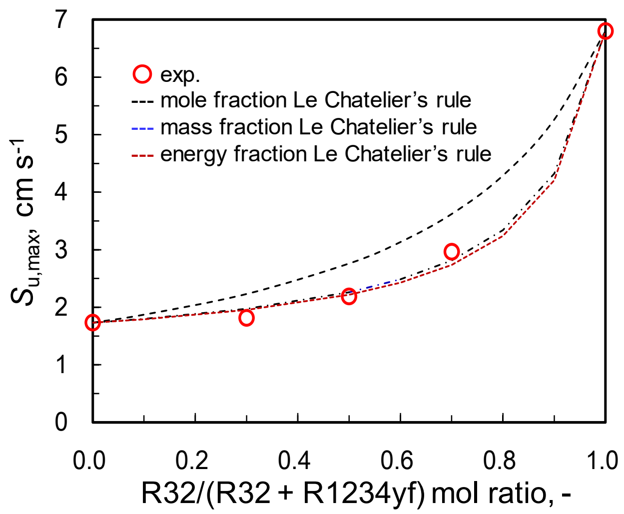


Fig. 5-3 Maximum burning velocities as a function of mixing ratio for R32/1234yf mixtures at 35°C and 0%RH.

5.3 Evaluation of quenching distance of low GWP mixed refrigerant

The quenching distance was measured to evaluate the ignition and quenching characteristics. We measured the R32/1234yf mixtures and verified the possibility of estimating the quenching distance for blends from the result of each single substance. First, we evaluated the effect of the mixing ratio on the quenching distance at an initial pressure of 2 atm and 3 atm for R32/1234yf mixtures (measurement temperature of 25°C and humidity of 0%RH). Figure 5-4 shows the test results and various estimation results using Le Chatelier's formula. The quenching distance of the mixtures can be well expressed by Le Chatelier's formula for the mass fraction or energy fraction using the result of each single substance. Utilization of a high-pressure condition enabled the measurement of the quenching distance of extremely low flammable refrigerant to a high degree of accuracy, and the tendency of the mixing ratio dependence was found to be similar to the burning velocity.

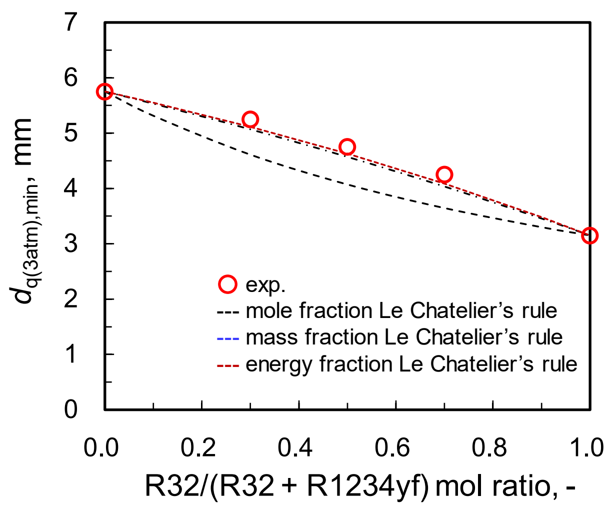


Fig. 5-4 Quenching distances of R32/1234yf mixtures measured at 3 atm, 25°C, and 0%RH.

We then evaluated the dependence of the quenching distance on the temperature, humidity, and mixing ratio for the R32/1234yf mixtures. Figures 5-5 and 5-6 show the results. It was found that the quenching distance of the mixture was larger than that of single R32 or R1234yf under the same conditions at the tested mixing compositions, similar to the conclusion of the burning velocity, and the ignitability of the mixture was equivalent to or lower than that of R32 or R1234yf under practical conditions. In addition, the quenching distance of this mixture can be mostly expressed by Le Chatelier's rules under high humidity conditions, as shown in Fig. 5-6.

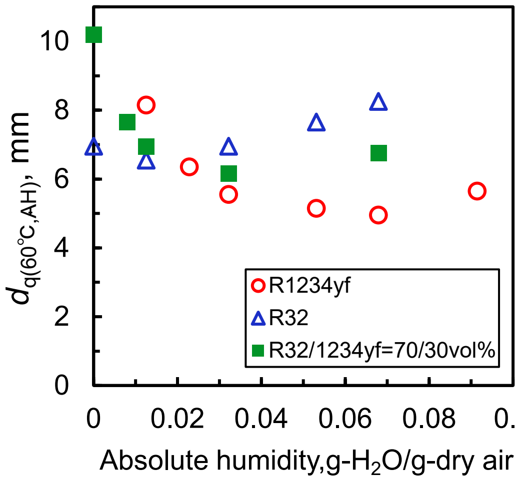


Fig. 5-5 Effect of humidity on d_q of R32, R1234yf, and R32/1234yf (70/30 v/v) mixture at T_0 = 60°C and P_0 = 1 atm.

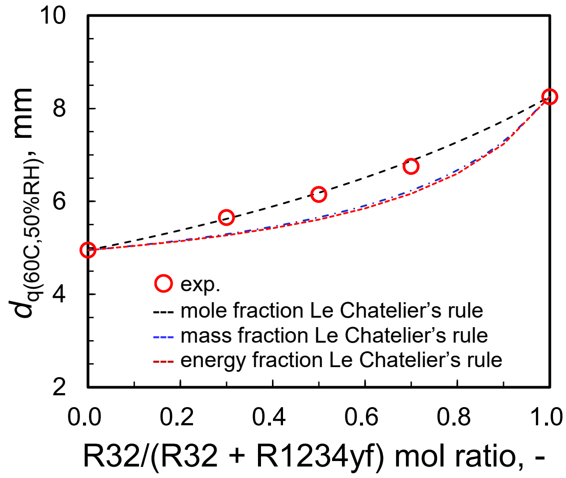


Fig. 5-6 d_q of R32/1234yf mixtures under high humidity (60°C and 50%RH).

6. Progress of risk assessment of mini-split air conditioners using A3 refrigerant conducted by JRAIA

JRAIA aims for the stepwise conversion to a low-GWP refrigerant to mitigate global warming and began the risk assessment of the mini-split air conditioner (hereafter air conditioner) using A3 refrigerant in July 2016. This risk assessment started as a NEDO project in the latter half of 2018 in collaboration with the government, academia, and industry, similar to the one with A2L refrigerant.

The risk assessment is being conducted for the air conditioners using A3 refrigerant and compared with one with R32. This report summarizes the content of the published reports of the JRAIA project regarding the safe use of A3 refrigerant in the last three years.

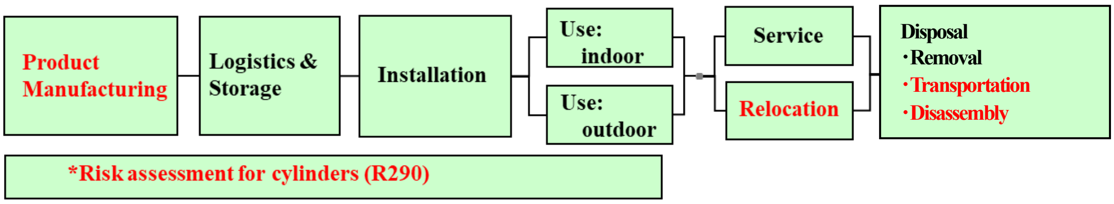
The risk assessment project is still in progress and the results have not been comprehensively reported yet. The results s of the project will be reported at the Kobe International Symposium (International Symposium on New Refrigerants and Environmental Technology 2021) in the official form in October 2021.

6.1 Scope of risk assessment

Generally speaking, a scope of a risk assessment is to be the entire life stages from manufacturing to disposal of a product. However, the scope of this risk assessment in this report is limited. Figure 6-1 shows the target stages of it that includes life stages of “transportation and storage,” “installation,” “indoor and outdoor risk during use,” “repair”, and “removal in disposal.” Items in red letters in Fig. 6-1 are outside the scope of the risk assessment.

The following are the reason why excluded and evaluation range of this risk assessment:

- Product manufacturing: Because each company has different manufacturing know-how and hard to generalize.
- Relocation of air conditioner: This is basically a combination of three stages—“removal”, "transportation" and "installation", so it is tentatively excluded due to lack of time.
- Disposal: It can be divided into removal, transportation to a recycling factory, and disassembly; however, this time, only removal is evaluated due to lack of time.



Note: The stages in red are not included in the JRAIA risk assessment.

Fig.6-1 Life stages covered by risk assessment

6.2 Indoor ignition source and refrigerant leak simulation during use

To obtain the probability of an ignition incident when the refrigerant leaks from the indoor unit, we investigated the formation of a flammable space using the simulation of refrigerant leakage and evaluated the ignition sources that exist indoors.

Simulation of refrigerant leakage from indoor unit

A room with the floor area of 7.0 m^2 is assumed here and the refrigerant charge of R290 is assumed 200 g, which is allowed when there is no safety measure in IEC 60335-2-40 Ed 6.0 (hereafter referred to as IEC standard) as the typical usage environment of the indoor unit. We also calculated a refrigerant charge of 500 g for products using R290, which provides equivalent performance as the products using 1000 g of HFC refrigerant. The floor area is assumed to be 11.88 m^2, which is the minimum floor area according to IEC60335-2-40 7^{th} edition draft with fan circulation. The ceiling height is assumed to be 2.2 m, and the indoor unit is assumed to have the bottom of it at 1.8 m from the floor. The time for entire refrigerant leakage is assumed to be in 4 min, as adopted in the IEC standard.

Leakage is anticipated to occur both during the off mode of the air conditioner (no agitation by fan) and operation (with agitation) mode. Mixtures of air and refrigerant is assumed to leak from the indoor unit. The airflow is assumed according to the formula of Colbourne et al. in the IEC standard.

Effect of agitation

Figure 6-2 shows the refrigerant concentration distribution at the end of the leakage (4 min after the leak start) by CFD analysis. Without agitation, a flammable space is generated from the indoor unit down to the floor and to a height of 0.008 m from the floor with 200 g of refrigerant charge. The height of it is 0.326 m with 500 g of refrigerant charge. With agitation in cooling mode, a flammable space was generated at a horizontal distance of up to approximately 0.1 m from the air outlet of the indoor unit with 200 g of the refrigerant charge (50 g/min release). It develops up to approximately 0.3 m with 500 g of the refrigerant charge (125 g/min release). The flammable space was generated in a similar range downward in case of heating operation because the air flow is directed downward for comfort in heating mode.

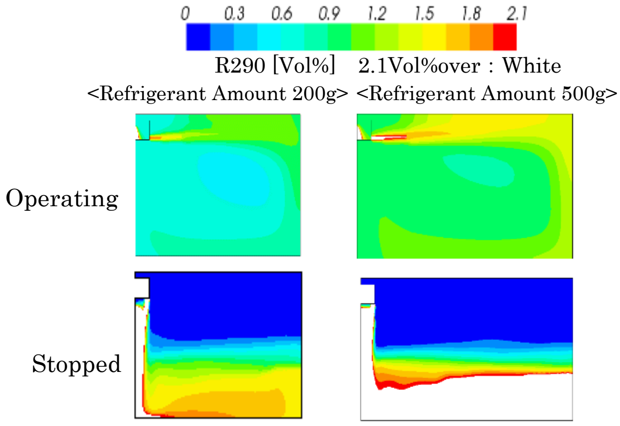


Fig. 6-2 Refrigerant concentration distribution after 4 min.

Effect of refrigerant charge amount

As mentioned above, because the refrigerant leaks directly below the indoor unit in the case of no agitation and the flammable region is formed from the floor surface, the flammable space volume divided by the floor area is the height of the flammable space. The flammable space volume increases quite rapidly once stagnated flammable space is generated on the floor. Up to that time, flammable space volume and duration are quite limited.

Identification of indoor ignition source

When identifying the ignition source, the flammable space height obtained by the refrigerant leakage simulation and the height at which the potential ignition source exists indoors are compared one by one. Without agitation by fan, because a flammable space was formed directly under the indoor unit to the floor surface, if the potential ignition source could be used directly under the indoor unit, it was specified as the ignition source.

The identified ignition sources were cigarettes, candles, gas cooking stoves and kerosene heater as naked flame sources, electric heaters, kotatsu, electric heaters, electric irons, hair dryers, as a high-temperature surface source, and laser printers, electric shavers, air purifiers, dehumidifiers, vacuum cleaners, electric carpets, lighting switches, and plugging to/unplugging from the socket as spark sources. On the other hand, candles, cooking stoves, cooking devices, static electricity released when contacting a doorknob, ON/OFF of lighting switches, etc., which have sufficient energy to ignite, were judged not to be ignition sources since the height of them are far above flammable space. Hereafter, we will assess the mitigation measure for these specified ignition sources, taking the results of other research projects in the NEDO into account.

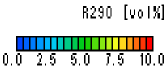
6.3 Outdoor refrigerant leak simulation during use

To obtain the probability of ignition accident associated with the refrigerant leak from an outdoor unit, the formation of a flammable space by outdoor refrigerant leakage is analyzed including the effect of the gap under a partition panel between neighboring balconies and the effect of wind. In addition, the ignition sources around outdoor units is studied here.

Simulation of refrigerant leakage outdoors

A balcony covered by walls in three directions of an apartment house is assumed as a typical case for installation of the outdoor units. Further, installation cases of directly on the floor surface, with double-stack installation and suspended installation are studied as the installation cases for an outdoor unit. Refrigerant leakage amount of 200 g, 500 g, and 1000 g are assumed while the leakage of the entire refrigerant is assumed to take 4 min also here. Further, we checked the effect of the gap under a partition panel between neighboring balconies that are often seen in apartments. The effect of wind is also assessed.

Effect of a gap under the partition panel between the balconies



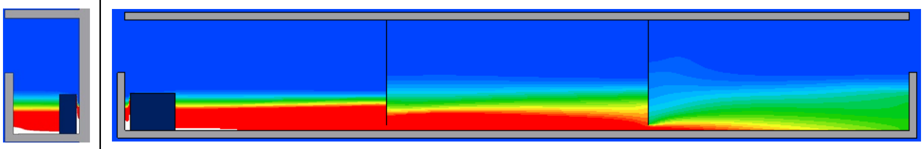
Leakage amount			Balcony 1	Balcony 2	Balcony 3
500 g	Concen-tration distribution	240 s			
	Duration		701 s	582 s	269 s
	Averaged volume		1.32 m^3	0.71 m^3	0.07 m^3

Fig. 6-3 Concentration distribution and the duration and time averaged volume of flammable regions within each balcony with partition panels

The leakage analysis of a balcony adjacent to 3 apartments with partitions with gaps of 0.1 m height showed that significant amount of leaked refrigerant flows to the neighboring balcony through the gap. The duration and average volume of the flammable space decreases significantly in comparison with the case without gap. When the refrigerant charge was 500 g and 1000 g, flammable space is formed up to the balcony of the third neighbouring apartment. Figure 6-3 shows a simulation result for a leakage amount of 500 g.

Effect of natural wind

The probability of wind velocity of the representative cities in Japan was investigated and found that wind velocity between 1.0 and 2.0 m/s has the highest probability. The probability of 0.0 m/s (no wind) is 0.5% on official record. This 0 m (no wind) in official record means average wind velocity in 10 min is less than 0.3 m. In other words, wind is considered to blow at a probability of 99.5% or more. Therefore, the refrigerant leak under wind blowing conditions are analysed and the probability of an ignition incident is calculated by multiplying the volume of combustible space under a certain wind speed and the frequency of occurrence of that wind speed, then probability of ignition under wind blowing condition is calculated by integrating them over the entire wind speed range.

. As a result, the ignition probability with wind consideration decreases to approximately 1/100 of one without wind consideration.

Effect of installation method

The results of refrigerant leakage analysis on installation method shows that the duration of the flammable space decreases as the installation height increases. In the case of upper installation of double-stack and ceiling suspended installation cases flammable space duration decreases significantly in comparison with the floor surface installation.

Evaluation of outdoor ignition sources

The open flame of combusting core part of a cigarette of a resident, cigarette lighter, burner of gas/petroleum water heater, and electric sparks due to switching of other air conditioners are assumed as potential ignition sources. The frequency and existing time of them are estimated by considering the actual state of the use and the principle of function of them. However, the results of a literature search showed that smoking and switching the outdoor unit of an air conditioner ON/OFF are not ignition sources for R290. We estimated that gas/petroleum appliances are not an ignition source because the refrigerant is agitated by the action of a burning fan before ignition. Therefore, it is necessary to calculate the probability of ignition accident generation by considering such opinions.

Directivity of safety measures for outdoor unit

As for safety measures, it was recognized that the establishment of an installation height limit for outdoor units, installation at a place with clearance, and installation at a place with good ventilation are effective for the suppression of flammable space generation.

As for safety measures for outdoor use, warning labels are actually considered to be a feasible safety measure, as described in the IEC standard, which also targets general users.

6.4 Thinking and proposal for unexpected events in risk assessment

Here, we describe an unexpected way of thinking and proposals concerning works and processes that are not normally considered.

Thinking for unexpected events in risk assessment

(i) Disposal and recovery

The recovery of refrigerants for air conditioners that are handled illegally at disposal is an unexpected event. According to a press release by Ministry of Economy, Trade and Industry (METI) and the Ministry of Environment, nearly 60% of air conditioners are recovered via hidden ways, and it is unclear whether the refrigerant is properly recovered and treated. Because the recovery of refrigerants results in the burden of treatment expenses, if it is released into the atmosphere, the possibility of an increase in ignition accidents cannot be denied. In addition, if useless article recovery companies perform reuse or scrap handling, similar risks also arise.

(ii) Installation and repair

This risk assessment presumes that workers who receive training to gain knowledge and technology install and repair air conditioners. However, untrained workers, such as do-it-yourselfer or moving companies, may relocate air conditioners. The actual situation is unknown. In addition, workers who have no secure safety knowledge concerning flammable refrigerants even now and who are almost amateurs with no knowledge about installation sometimes use an incorrect type of refrigerant outside of the responsibility of the air conditioner manufacturer. When they work rapidly during busy seasons, this results in personal mistakes, which may lead to serious accidents, and the frequency of these occurrences is not clarified.

(iii) Unexpected accident phenomena.

Generally, the intentional arson of the outdoor unit of an air conditioner and the carrying-away of an outdoor unit currently in operation are unexpected in the risk assessment.

As mentioned above, it is easy to imagine that these unexpected events will increase the number of ignition accidents. Furthermore, the quantification of danger is difficult. Moreover, there are tasks concerning security and safety, as well as any violations of other items.

Proposal for unexpected events in risk assessment

Risk assessment takes the position of using new products and technology with an allowable danger generation probability, and it is obvious that risks remain if the generation probability is less than a certain value. Therefore, to better understand the difference between safety and security, risk management needs to be further studied. On the other hand, recommendations for unexpected events described in the previous section will also be an important issue in the future. Further, it does not mean that an unexpected event was considered in the risk management of an air conditioner that used A2L refrigerant R32, which is currently widespread in the market. Nevertheless, ignition accidents were not actually generated. This is because (i) R32 has fewer types of ignition sources in comparison with the A3 refrigerant even if unexpected events previously enumerated exist, (ii) the minimum ignition energy is high, and (iii) the formation of a flammable region is extremely difficult, as the LFL is 13.5%. On the other hand, in the case of R290, it is estimated that the flammable region is easily formed in comparison with R32 because R290 has many ignition sources, the minimum ignition energy is as small as approximately 1.25% of that of R32, and the LFL is as low as 2.02%. Therefore, to commercialize R290, it is important to eliminate unexpected events in risk assessment.

Measures for commercializing R290 as a refrigerant are proposed below:

① Enhancement of approaches for allowing air conditioner refrigerant to be recovered and treated appropriately

An examination of the infrastructure improvement concerning the recovery and treatment of refrigerants for air conditioners, including the home appliance recycling system, is necessary. Safety security is particularly essential for human intervention. If such a measure is not effective, an examination of a new social system should be initiated.

② License system for workers who install and repair air conditioners

A new mechanism whereby an association related to refrigeration air conditioning provides training courses and improves the qualification system for flammable refrigerant work based on practical training or establishes a licensing system based on a legal background.

Although the above measures are to avoid any unsafe work and action that should be eliminated, risk assessment for labor safety and machinery safety requires securing safety based on the assumption that "human always make mistakes" and "machinery failure always occurs", as described in the international standard ISO 45001 and ISO 12100, as well as in JIS Z8115. In the case of adopting R290 as a refrigerant, it is necessary to return to this origin and consider measures that will not harm people even if an ignition accident occurs or consider measures so that an ignition concentration region will not be formed even if the refrigerant leaks. To further improve safety, we would like to consider measures such as wearing protective equipment during work, appropriate means of stopping equipment in the leak event, and appropriate refrigerant release measures during removal.

When using R290 in a real society, the viewpoints of safety and security are important. To deepen the understanding of the differences between these matters, enlightenment activities related to risk management and close risk communication from the perspective of safety and security are essential.

7. Progress of risk assessment of refrigerated display cabinets using A3 refrigerant conducted by JRAIA

Refrigerated display cabinets with a built-in condensing unit (built-in refrigerated display cabinet) are used in restaurants, food stores, supermarkets, etc., and a shift to low-GWP refrigerants is desired in response to the Kigali Amendment to the Montreal Protocol. Therefore, in June 2019, International Standard IEC 60335-2-89 was revised to Edition 3.0, and the maximum refrigerant charge of A3 refrigerants was relaxed from the conventional 0.15 kg to approximately 0.5 kg (in case of R290). Since July 2016, the JRAIA has been performing analyses of the refrigerant leakage and risk assessments, assuming leakage from the inside and outside of a built-in refrigerated display cabinet using A3 refrigerants such as R290 and examining the methods for safely operating built-in refrigerated display cabinets using A3 refrigerants. The contents of the study are summarized below:

7.1 Main revision points of International Standard IEC60335-2-89

(1) It was determined that the flammable refrigerant can be charged up to 13 times the LFL or 1.2 kg, whichever is smaller. In the case of R290, because the LFL is 0.038 kg/m^3, it can be charged up to 0.494 kg.

(2) A room installed with an appliance using flammable refrigerant should have a floor area equal to or greater than the minimum room floor area for which the amount of refrigerant is a quarter of the LFL for the volume of the room. In the case of an appliance charged with 0.494 kg of R290, the appliance should be installed in a room with a floor area of 23.7 m^2 or more.

(3) When a refrigerant equal to or more than 0.15 kg was charged in the refrigerant circuit, a specified refrigerant leak test was carried out to verify that no flammable region was generated around the appliance. However, because the concentration measurement was exempted for 5 min from the start of measurement, the flammable region was deemed not to have been generated even if a large flammable cloud was generated during this time.

7.2 Analysis of refrigerant leakage

(1) When the door was rapidly opened after leakage into the refrigerated space in a reach-in refrigerated display cabinet, a flammable region was always generated outside the refrigerated display cabinet, and the maximum flammable volume hardly changed even by varying the air flow rate of the condensing unit and floor area. There is a possibility that the existence of an ignition source in the flammable region easily leads to ignition, even if the generation of a flammable region occurs in a short time in the case of A3 refrigerants. However, the IEC Standard deems it safe even if a large flammable cloud is generated within 5 min from the start of the door opening.

(2) In the case of leakage from the condensing unit of a horizontal refrigerated display cabinet, setting the air flow rate equal to or more than the specified value resulted in no generation of the flammable region.

(3) Refrigerant leakage from the reach-in refrigerated display cabinet in an enclosed space was analyzed, and the approximate equations for the duration of the flammable region and the mean flammable volume when the airflow of the condensing unit was present and was not present without the internal air curtain were obtained. In addition, approximate equations were obtained for the duration of the flammable region, and the mean flammable volume when the airflow of the condensing unit was zero for leakage from the condensing unit of the horizontal refrigerated display cabinet. These equations will be used for risk assessment.

(4) When R290 leaks from the condensing unit at the bottom of the refrigerated display cabinet, the value of the flammable volume-time integration hardly decreases even if the leak rate is considerably slow. Therefore, it is necessary to calculate the ignition probability considering all leaks, including slow leak, in the case of A3 refrigerants. Therefore, for safety, the refrigerant leak rate from a built-in refrigerated display cabinet to be used for risk assessment is assumed to be the value at which the total refrigerant amount leaked in 4 min used in International Standard IEC 60335-2-40 for air conditioners. This setting can be said to have no significant problems.

(5) Concerning refrigerant leakage from the refrigerated space of a vertical refrigerated display cabinet, if a specified value of the airflow of a condensing unit at the bottom of the refrigerated display cabinet is secured, a significant

flammable region resulting in ignition is not generated outside the refrigerated display cabinet.

7.3 Condition and method for risk assessment

The ignition probability of an appliance using a flammable refrigerant is calculated by multiplying the temporal encounter probability, which is the time rate of the contact of the ignition source with the flammable region with the spatial encounter probability representing the space distribution of the flammable region and the refrigerant leakage probability. At this time, the approximate equation obtained from the results of the refrigerant leak analysis is used for the duration of the flammable region and the mean flammable volume. A modeled store for which risk assessment was carried out was assumed to be a convenience store in which simple cooking such as frying was possible, the amount of refrigerant in the refrigerant circuit in the refrigerated display cabinet was assumed to be 0.5 kg, and the floor area inside the store was assumed to be 84.7 m^2. The life stage of the built-in refrigerated display cabinet was set for transportation, storage, installation, usage, repair, and removal, and the assumed contents of the scenario for each stage were explained. Concerning ignition sources during usage, the details of the study of an electric spark of each electrical device, static electricity, open flame, etc. were explained.

7.4 Japanese law (High Pressure Gas Safety Act)

Under the High Pressure Gas Safety Act, high-pressure gas in the refrigerant circuit with a refrigerating capacity of less than 3 legal tons is exempted from the law. However, this concerns only the Refrigeration Safety Regulation. Excluding refrigerants applied with the Refrigeration Safety Regulation, for a refrigerant in which the main component is hydrocarbons with a carbon number of 3 or 4, the Liquefied Petroleum Gas Safety Regulation applies, and for other refrigerants, the General High Pressure Gas Safety Regulation applies. If the General High Pressure Gas Safety Regulation or the Liquefied Petroleum Gas Safety Regulation applies to the release of refrigerant into the atmosphere from the refrigerant circuit of an appliance (disposal of refrigerant), the recovery of the refrigerant and the charging of the refrigerant into an appliance, a notification report to regulatory authorities is required 20 days in advance, which makes the repair of an appliance substantially impossible. Therefore, JRAIA repeated negotiations with the High Pressure Gas Safety Office of the METI to relax this. As a result, concerning the release of refrigerant into the atmosphere (disposal of refrigerant) and the charge, the High Pressure Gas Safety Office of METI announced the following judgment in July 2020. Thus, the disposal and charge of the refrigerant on site becomes possible without the need to submit a notification report for repair.

> "Regarding the disposal of refrigerant from refrigerating equipment with refrigerating capacity of less than 3 legal tons due to pressure difference and the charge of refrigerant to a refrigerating equipment with refrigerating capacity of less than 3 legal tons due to pressure difference are exempted under the High Pressure Gas Safety Act. At this time, a treatment facility for changing the pressure shall not be used."

Further, concerning the recovery of A3 refrigerant, a notification report to regulatory authorities is required 20 days in advance, and the recovery of A3 refrigerant cannot be substantially impossible prior to repair because the exemption of application of the High Pressure Gas Safety Act does not apply.

7.5 Japanese Standard

JIS C 9335-2-89 is the Japanese Standard established by translating IEC 60335-2-89 and adding the necessary deviation (difference from the international standard). JRAIA prepared the draft, and the revision was performed in accordance with Edition 3.0 of IEC 60335-2-89. JRA 4078 and JRA GL-21 are the standards of JRAIA based on the risk assessment of built-in refrigerated display cabinets, etc., using A3 refrigerant. JIS C 9335-2-89 and JRAIA Standards (JRA 4078 and JRA GL-21) are generically called Japanese standards. The main contents of these standards are as follows:

(1) The flammability of A2L refrigerants is lower than that of A2 and A3 refrigerants. Because the maximum refrigerant charge is 1.2 kg according to the provision of IEC 60335-2-89, the A2L refrigerant cannot be used for large appliances. However, the International Standard IEC60335-2-40 for air conditioners relaxes the charge of the A2L refrigerant in comparison with A2 and A3 refrigerants because of the difference in flammability. Therefore, the Japanese Standard eliminated the upper limit of 1.2 kg and enabled the charging up to 13 times the LFL for all refrigerants.

(2) The provision of IEC 60335-2-89 prohibits the temperature of a surface exposed to leaked flammable refrigerant to exceed the auto-ignition temperature of the refrigerant reduced by 100 K. However, the International Standard

IEC60335-2-40 for air conditioners permits a surface temperature of up to 700°C for A2L because the refrigerant has a lower flammability. Therefore, the Japanese Standards specified that A2 and A3 refrigerants should not exceed the auto-ignition temperature of the refrigerant reduced by 100 K and the A2L refrigerant should not exceed 700°C.

(3) Analysis of the refrigerant leakage clarified that when a door is opened after the leakage of the total amount of refrigerant into the refrigerated space of a reach-in refrigerated display cabinet, a large flammable cloud is generated outside the refrigerated display cabinet. According to the provision of IEC, there is a measurement exemption time of 5 min, and the generation of the flammable region during this time is neglected. In the case of A3 refrigerants, because static electricity and relays of electrical devices are ignition sources, if a flammable region is generated even for a short time, there is the possibility of an ignition accident occurring. Therefore, the Japanese Standard eliminated the measurement exemption time of 5 min and provided that the generation of the flammable region was not allowed from the start of the test. Further, it provided the means for detecting leakage into refrigerated space and the device for shutting off the refrigerant circuit in order to prevent the generation of a flammable region outside the refrigerated display cabinet.

(4) IEC 60335-2-89 has no provision for securing safety during work. JRA Standard (JRA GL-21) provided content for reducing the ignition risk by using gloves to prevent electrostatic discharge and a portable leak detector to be carried. In addition, it provided the elimination of ignition sources from around the appliance and sufficient ventilation at the time of disposal and charge of the refrigerant when performing repair of the refrigerant circuit on site.