National Institute of
Advanced Industrial Science
and Technology
AIST

1.4

ICR2015 Workshop on Risk Assessment of
Mildly Flammable Refrigerants, August 20, 2015

4. Fundamental and Practical Flammability Properties of 2L Refrigerants

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Overview

1. Background

2. Fundamental flammability properties

3. MIE and quenching distance

4. Flame extinction diameter

5. Summary

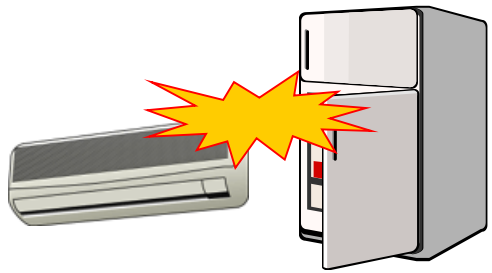
1. Background
 - Importance of evaluating low flammability

2. Fundamental flammability properties

3. MIE and quenching distance

4. Flame extinction diameter

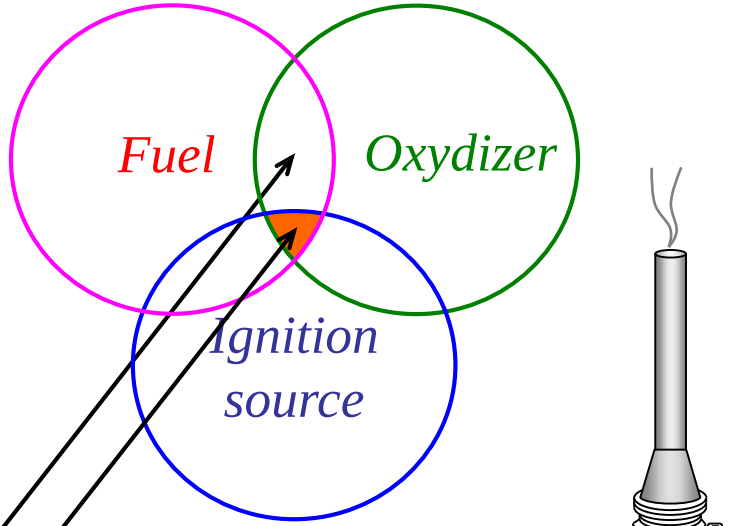
5. Summary



Flammability properties, indices of fire risks

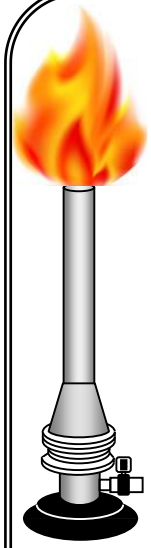
Risk ≡ combination of probability of occurrence of harm and severity of that harm*

Probability of fire



- **Flammability limits**
- Minimum ignition energy (MIE)
- Autoignition temperature
- ....

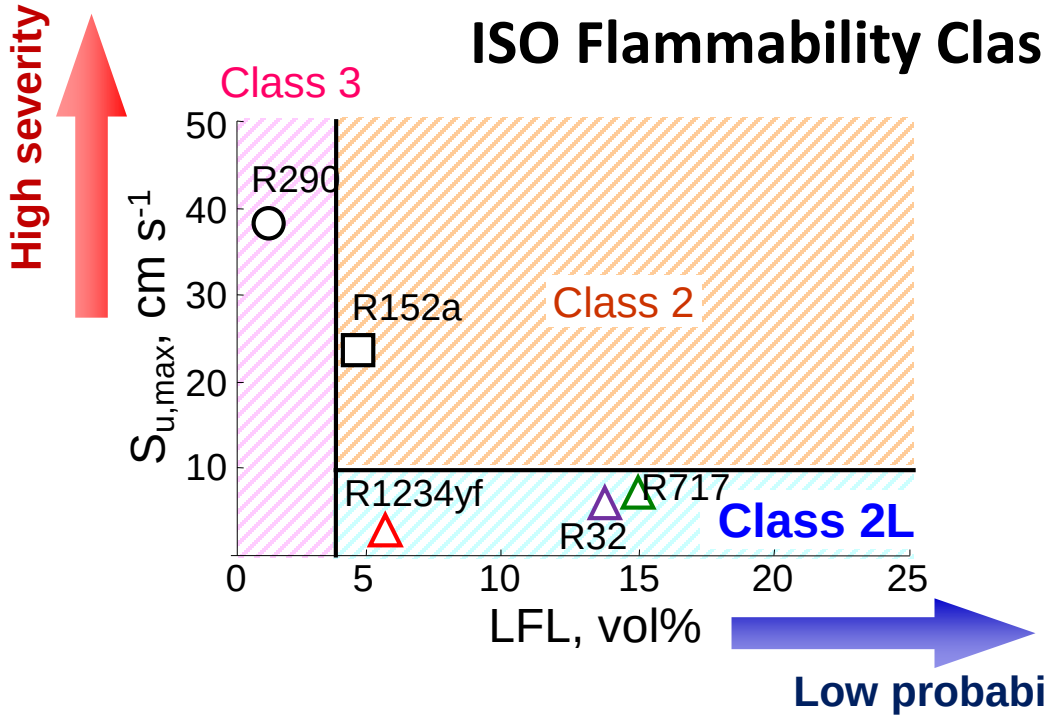
Severity of fire



- **Burning velocity**
- **Heat of combustion**
- Pressure rise rate
- Heat release rate
- ....

*ISO/IEC Guide 51, Safety aspects-Guidelines for their inclusion in standards (1999)

What is class 2L refrigerant?

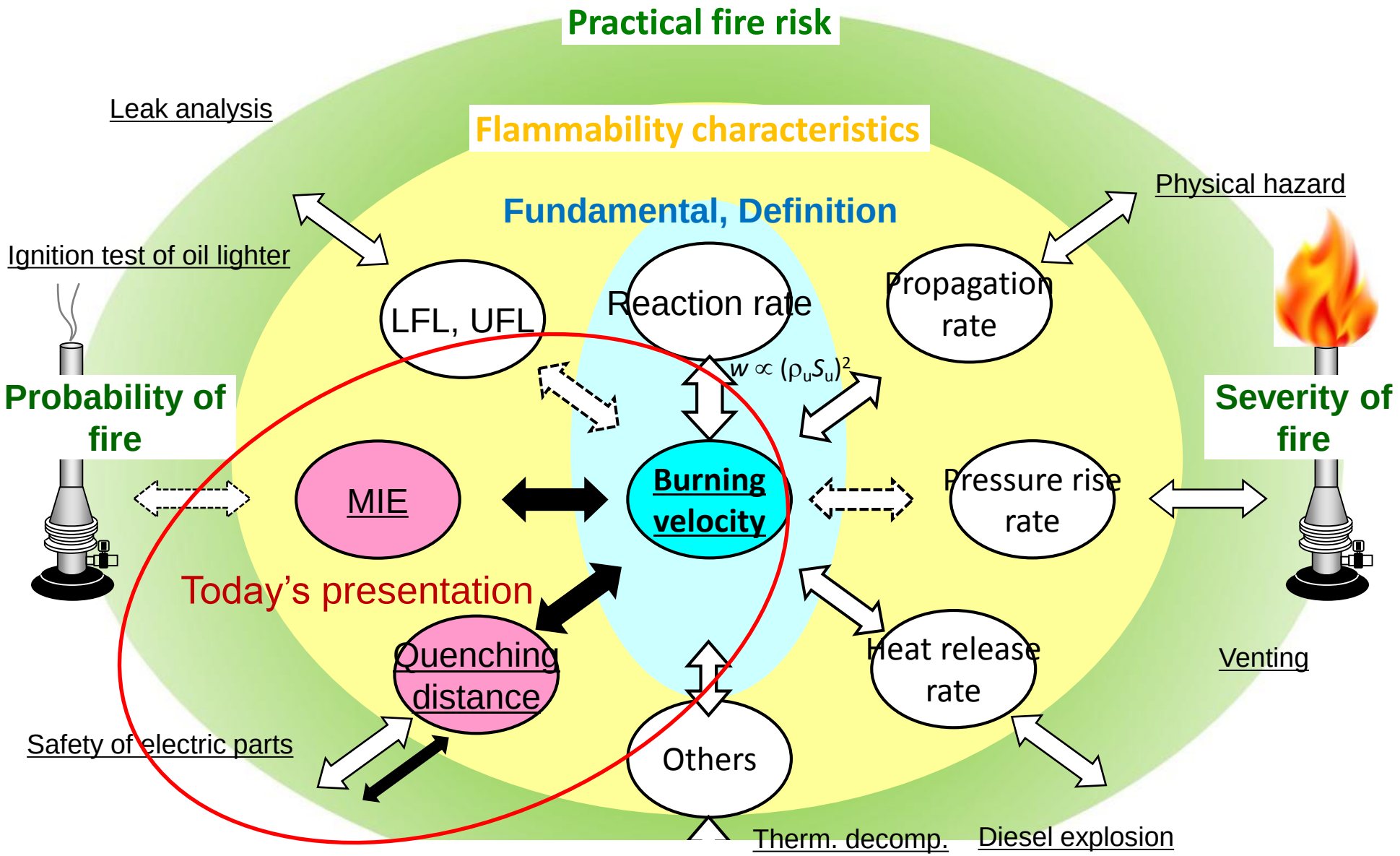


- LFL ≤3.5 vol% or Hc ≥19 MJ kg^{-1}
  → Class 3
- In Class 2, BV ≤10cm s^{-1}
  → **Class 2L**
- No flame propagation
  → Class 1

- Class 2L is the least flammable refrigerant class
- Low GWP 2L refrigerants are now considered as promising alternatives
- Flammability properties should be studied to characterize 2L for further understanding their practical risks

*ISO 817, Refrigerants— Designation and safety classification (2014)

Objectives



- Draw relationships between fundamental, various characteristics, and practical risks for wide variety of flammable refrigerants

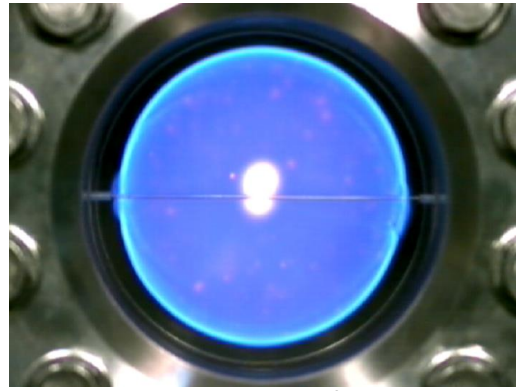
1. Background

2. Fundamental flammability properties
- Flammability limits
- Burning velocity

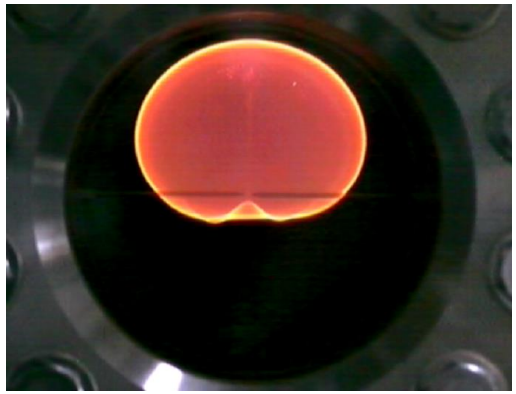
3. MIE and quenching distance

4. Flame extinction diameter

5. Summary



40 cm s^{-1}



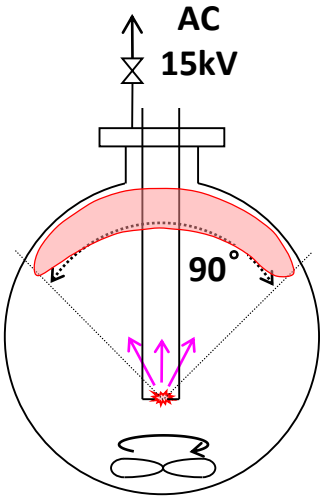
5 cm s^{-1}

1.5 cm s^{-1}

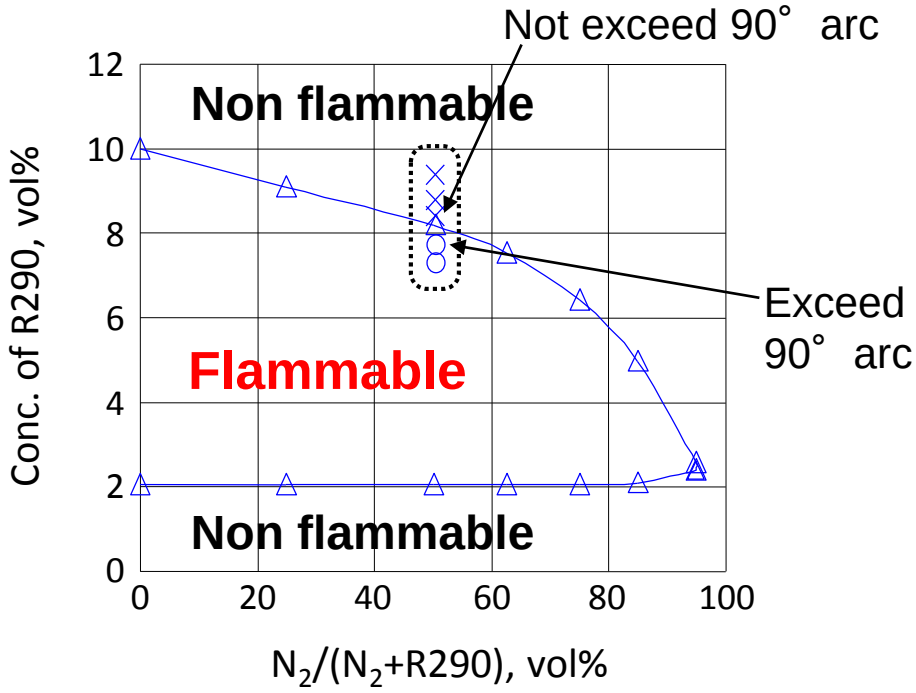
Flammability limits measurement

ASHRAE method* (1)

Test apparatus



Results of R290/Nitrogen/ Air



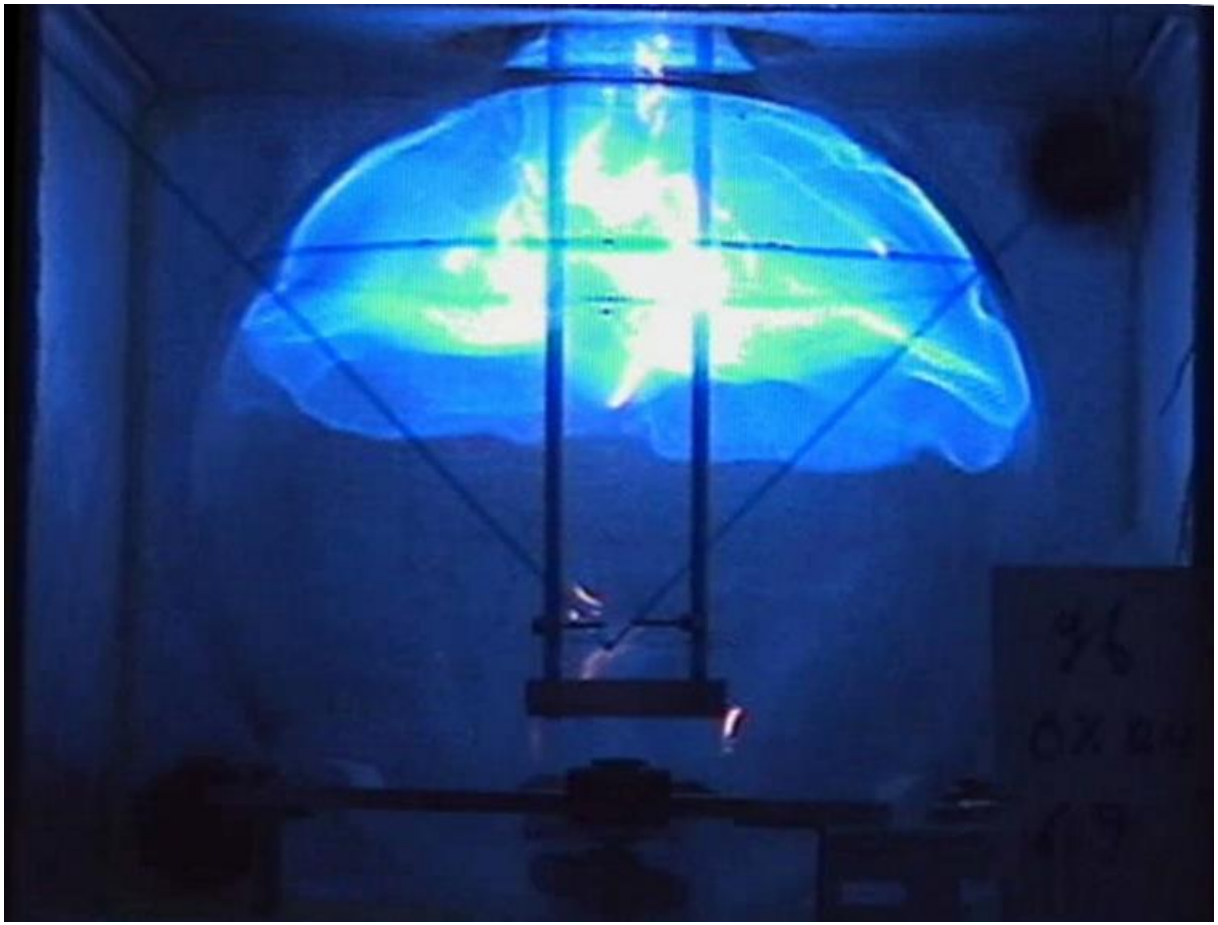
➢Flame propagation is determined by 90 degree criterion measured from the point of ignition to the walls of the flask

*ANSI/ASHRAE Standard 34, Designation and safety classification of re

Flammability limits measurement

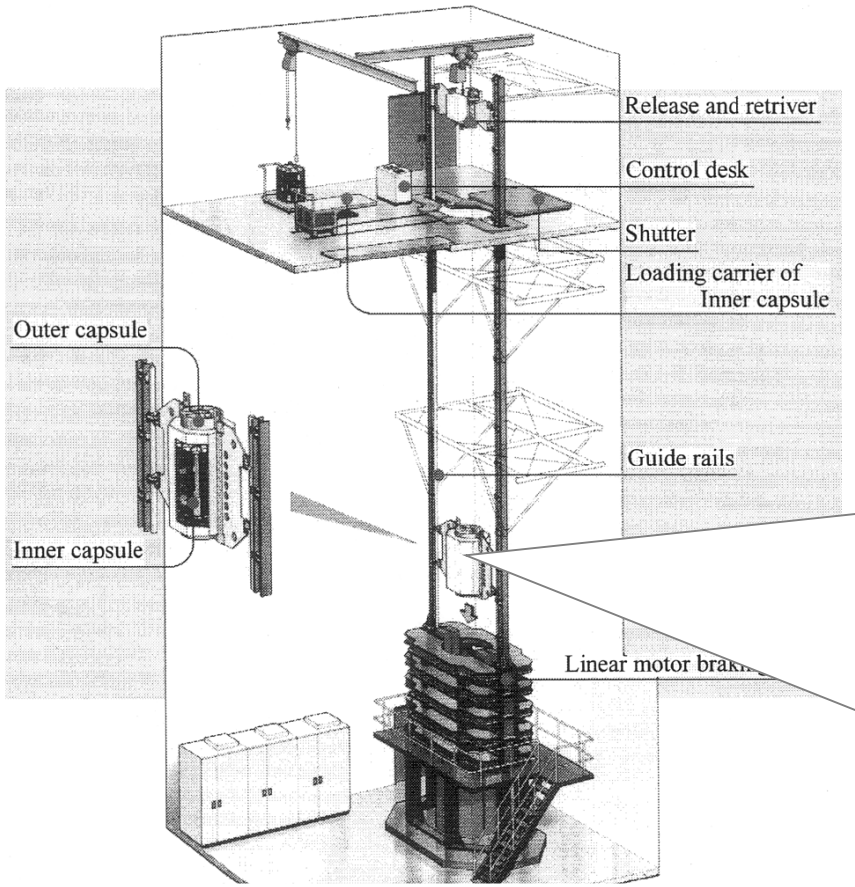
ASHRAE method (2)

Results for R1234yf (CH_2=$CFCF_3$) At 35 °C and 0% RH



Burning velocity measurement in microgravity (μg)

By removing gravity, we obtain “ideal” spherically-propagating flame



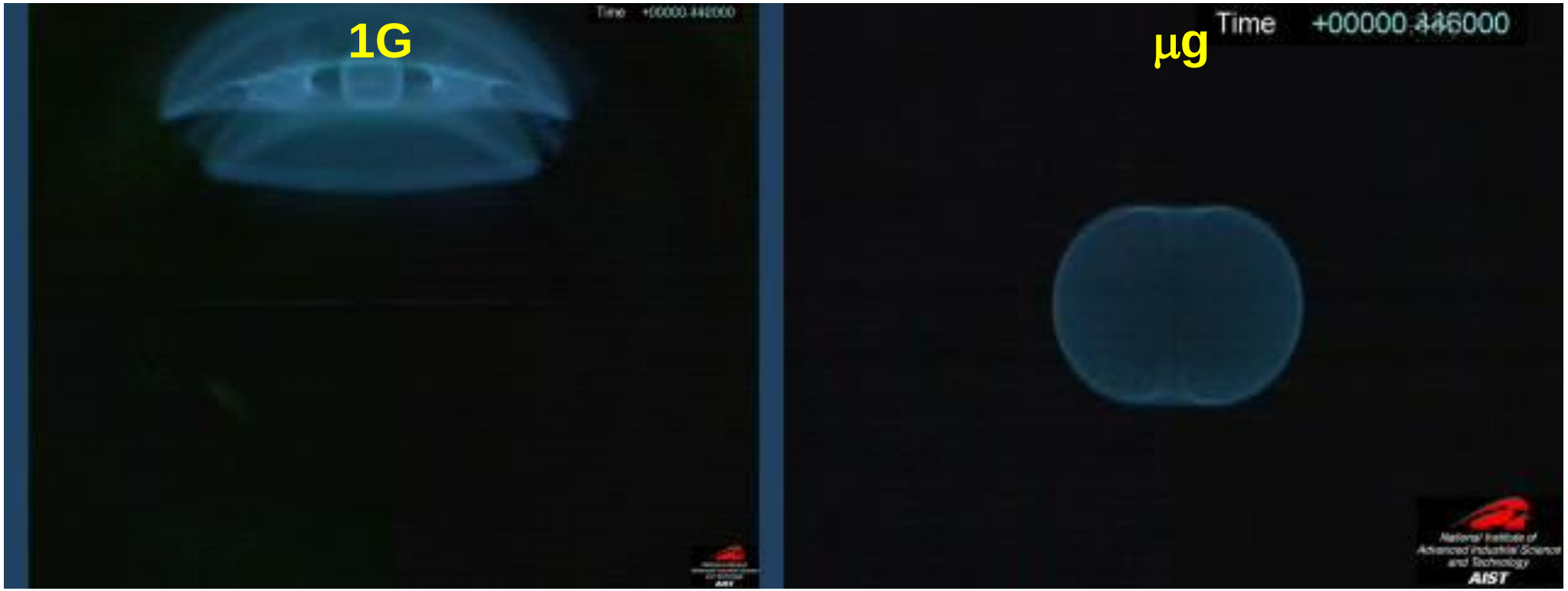
10-m drop tower in AIST

Apparatus in the inner capsule in the outer capsule

➢Flame propagation can be expressed by established spherical flame models

Flame propagation in μg

R1234yf (CH_2=$CFCF_3$), $S_{u,max}$ = 1.5 cm s^{-1}

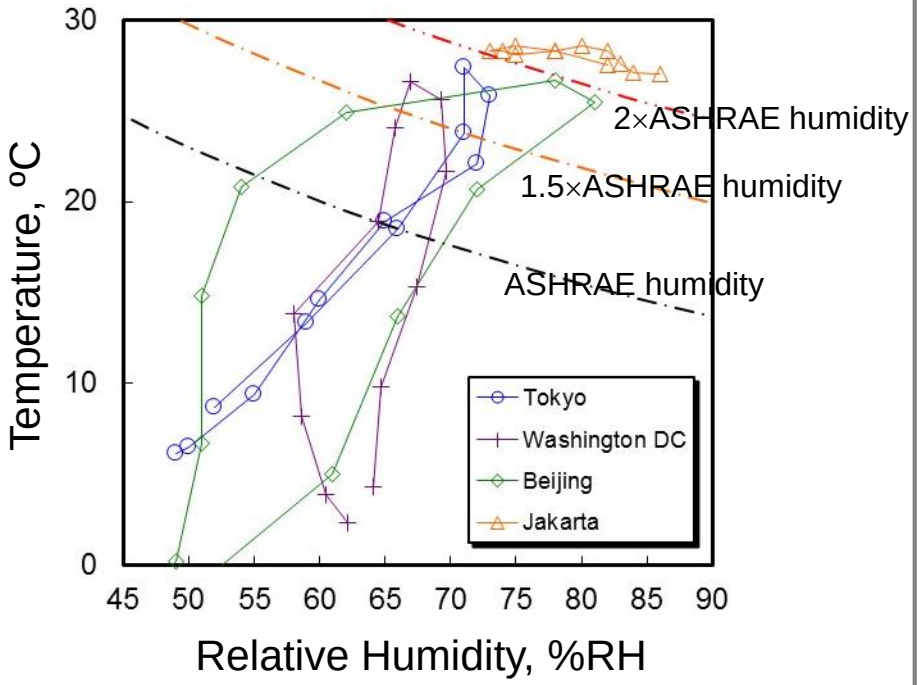


By using μg environment, we obtain

- spherically-propagating flame without affecting buoyancy nor wall quenching
- S_u from highly to only mildly flammable compounds by a single test method

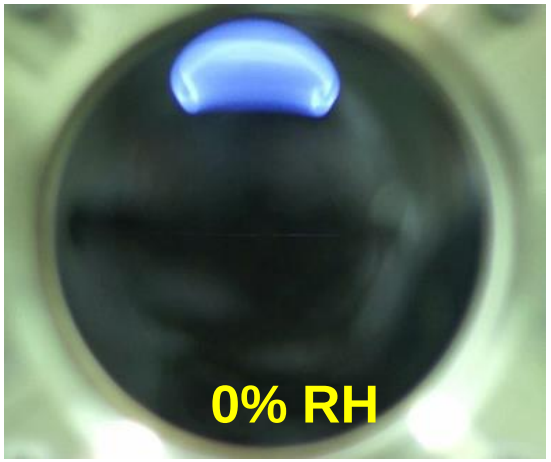
Humidity effects on flammability

Monthly average weather of four capitals

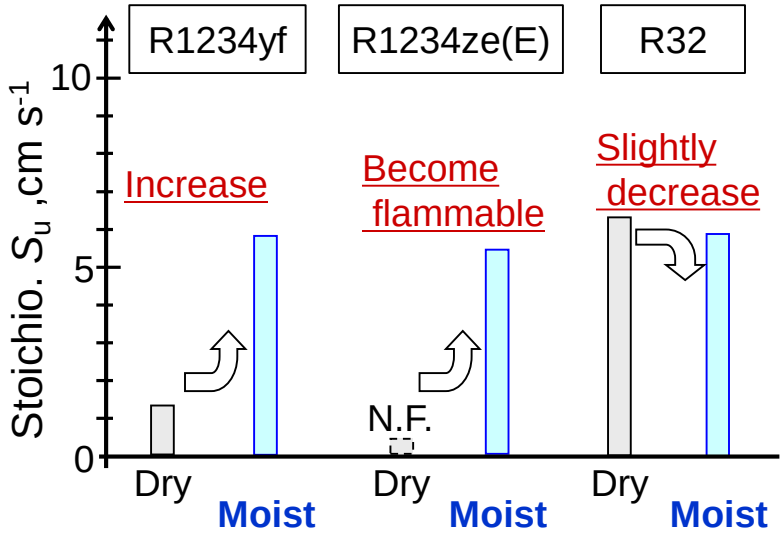


- Humidity level in the current standard is not high enough for high humidity areas of the world
- We are studying comprehensively on humidity effects on flammability

R1234yf flame with and without moisture



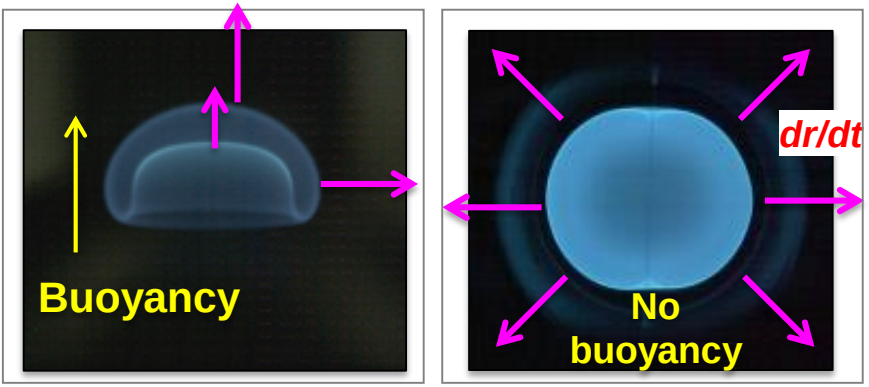
Humidity effect on Burning velocity



➢ Humidity **increased** S_u of R1234s

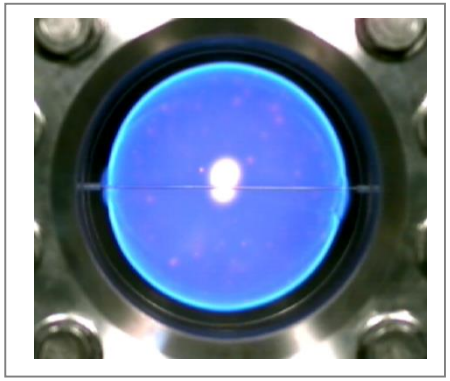
Summary of Part 2

2L flame (R1234yf)



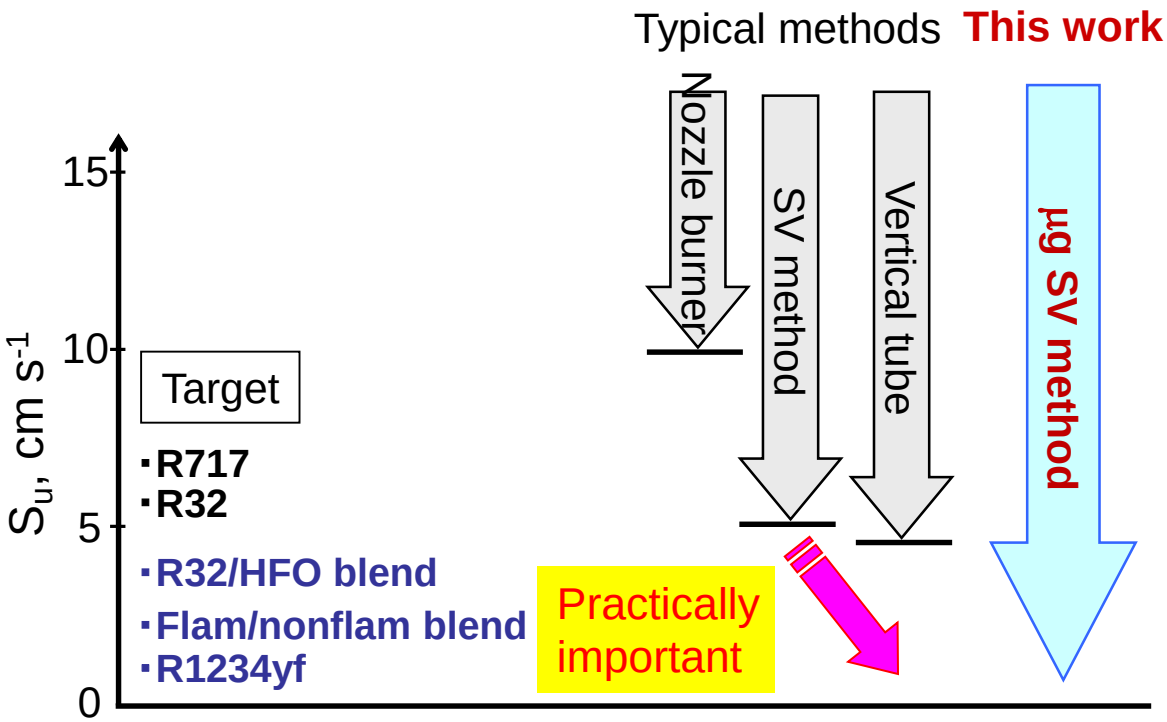
in 1G

in μg



R290 flame in 1G

Measurable S_u range



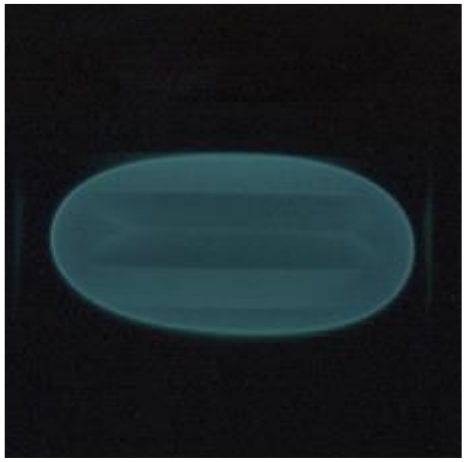
- By using μg environment, we evaluate S_u from highly to only mildly flammable compounds

1. Background

2. Fundamental flammability properties

3. MIE and quenching distance*

- Potential ignition sources
- Difficulty in MIE measurement
- Ignition and quenching of minimum flame
- Quenching distance measurement
- Estimation of MIE



QD measurement of R1234yf in μg

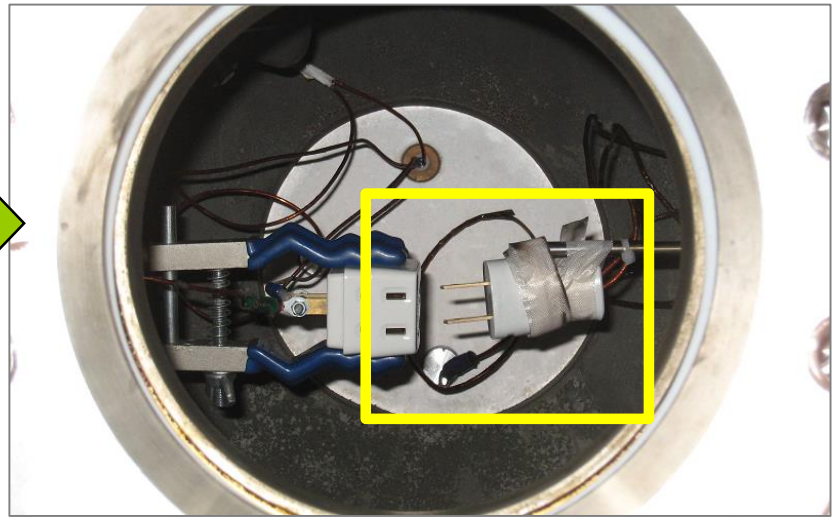
4. Flame extinction diameter

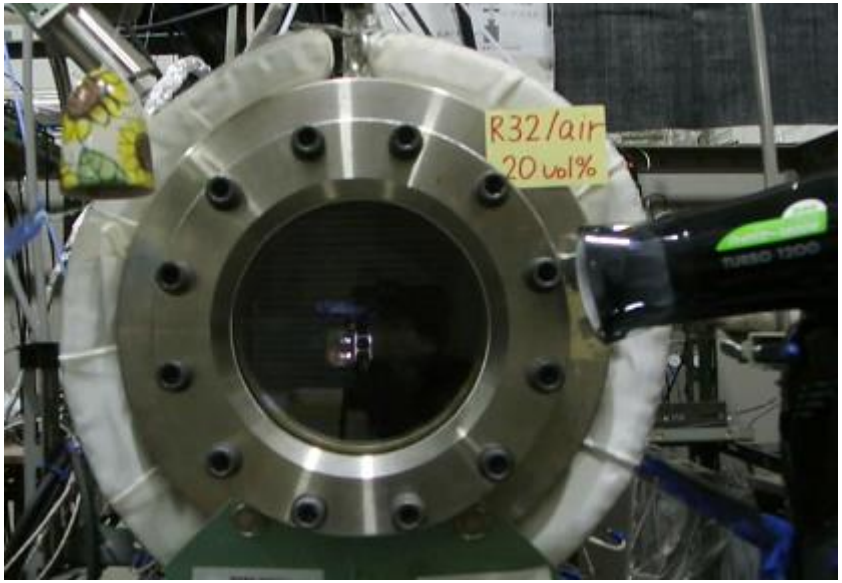
5. Summary

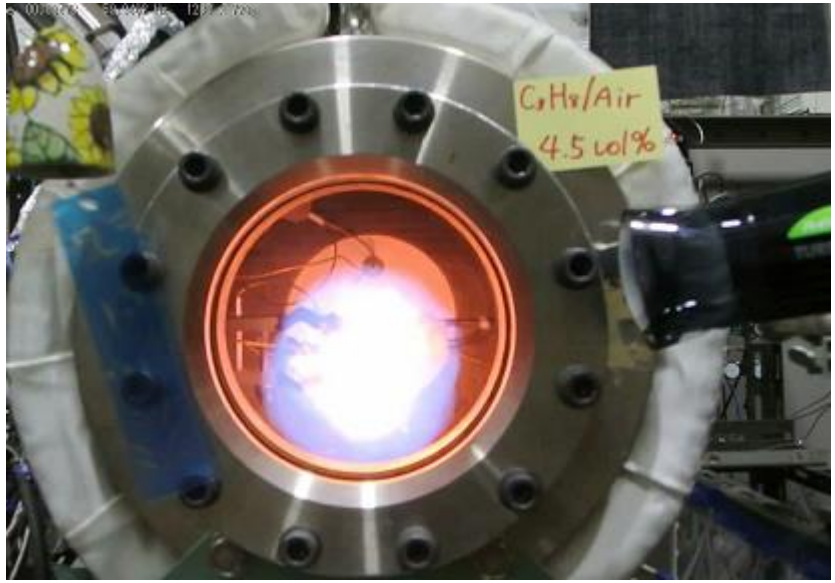
*See also, K. Takizawa et al., Quenching distance measurement of highly to mildly flammable compounds, Fire Safety J., 71, 58 (2015).

Background: potential ignition sources of refrigerants

Indoor unit





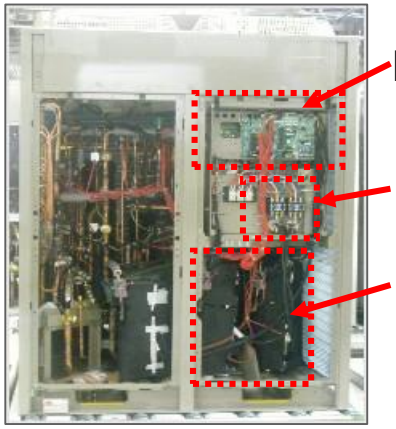


➢2L refrigerants were not ignited by spark of hairdryer (1200W, ca. 0.2-0.4J)

Potential ignition sources of refrigerants

Outdoor unit

Example of AC outdoor unit

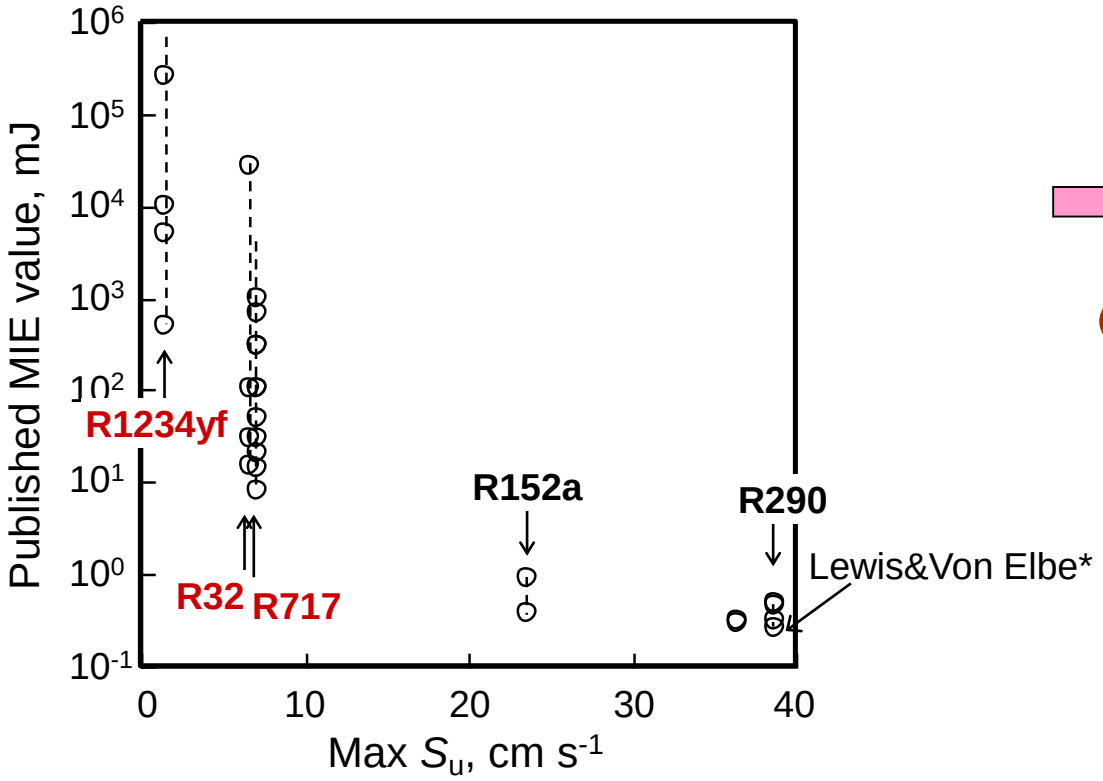


Ignition test using MC
(60A、220V load)

- Electromagnetic contactor (MC) is an important potential ignition source that may exist in high concentration refrigerant
- R32 and R1234yf were not ignited by spark of AC220V and 60A load (ca. 4J > E_{min})
- To understand these results, ignition and quenching characteristics for 2L should be accumulated

Difficulty in MIE measurement

Wide variations of published MIE values



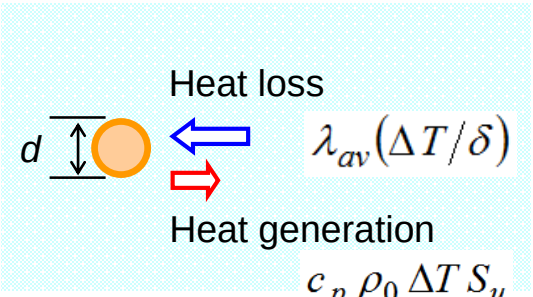
For 2L refrigerants,
variation of MIE is three orders!

- Variation of reported MIE values is very wide, which makes it difficult to use MIE as a flammability index
- To obtain reliable MIE is important to improve the current situation

*B. Lewis, G. von Elbe, “Combustion, Flames and Explosions of Gases”, third ed. (1987).

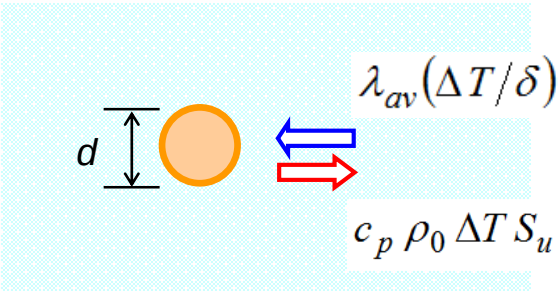
Ignition and quenching of minimum flame

(1) $d < d_q$



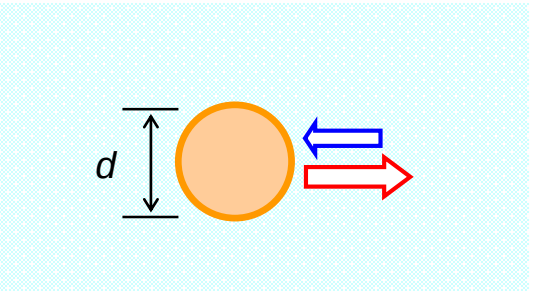
→ Extinction

(2) $d = d_q$



→ Minimum flame diameter
≡ **Quenching distance (d_q)**

(3) $d > d_q$

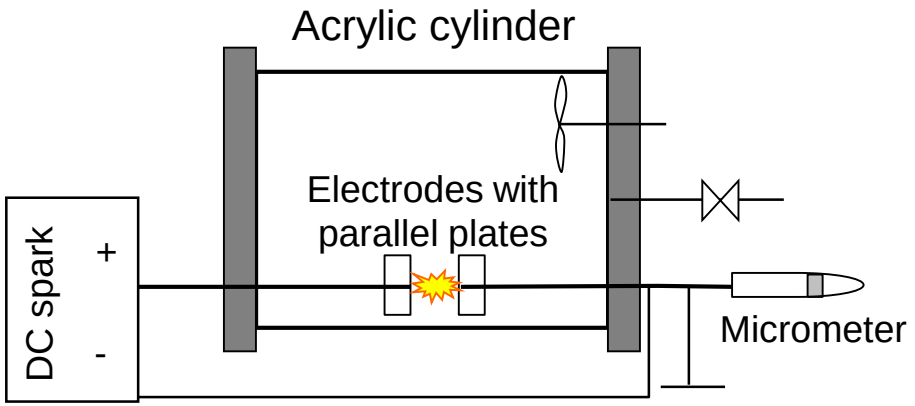


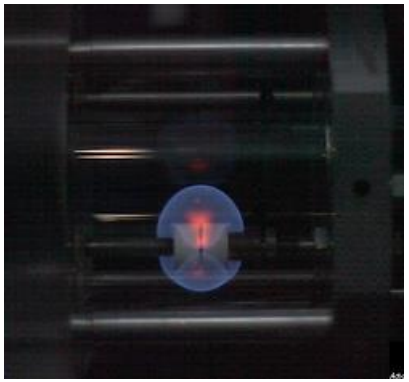
→ Self-sustained propagation

Terms	Definition	Equation
Ignition	To supply to the combustible mixture sufficient energy to create a kernel of hot gas that satisfies the necessary condition for self-propagation	
Quenching distance (d_q)	Critical size that the inflamed volume must just exceed in order to propagate unaided	$d_q = a\,(\lambda/C_P\rho_0 S_u)$
Minimum ignition energy (E_{min})	The amount of energy that the spark must supply for the hot kernel to attain this critical size (d_q)	$E_{min} = (1/6)\,\pi\,d_q^3\,\rho_0\,C_P\,\Delta T$

➢ We estimate MIE by obtaining QD and employing heat loss theory

Quenching distance measurement





R290, d =1.7 mm

➢Considering wide use of the test method and values, we tested various conditions:

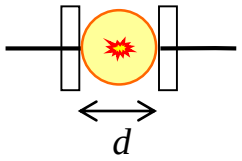
1. Compound

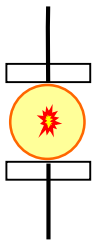
- ✓R290
- ✓R600a
- ✓R152a
- ✓HFO-1243zf
- ✓HFC-143
- ✓R152a/134a (50/50 v/v)
- ✓**HFC-254fb**
- ✓**R717**
- ✓**R143a**
- ✓**R32**
- ✓**R1234yf**

×

2. Configuration of parallel plates

✓ Vertical position* ✓ Horizontal position





✓ Under microgravity

×

3. Type of ignition spark

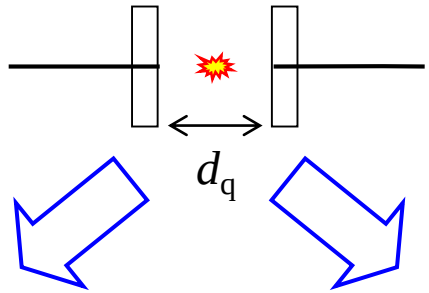
- ・AC spark
- ✓Neon transformer
- ✓Duration of 100 ms
- ✓Energy of 2.5 J

- ・DC spark
- ✓Duration of 1-10 ms
- ✓Energy of 0.1-5 J

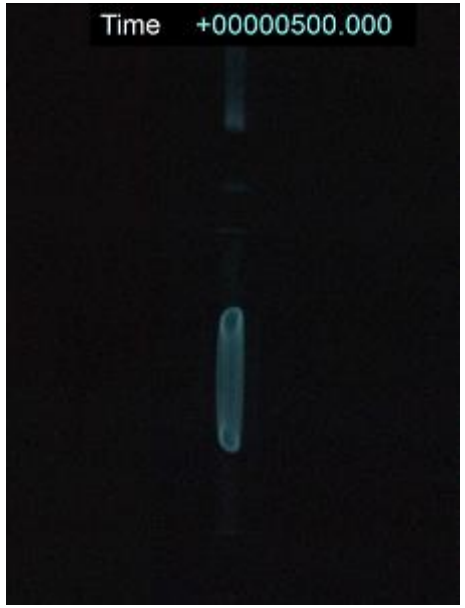
*ASTM E582-07 “Standard Test Method for Minimum Ignition Energy and Quenching Distance in Gaseous Mixtures” (2007)

QD measurement in μg

-R1234yf, 10 vol%-

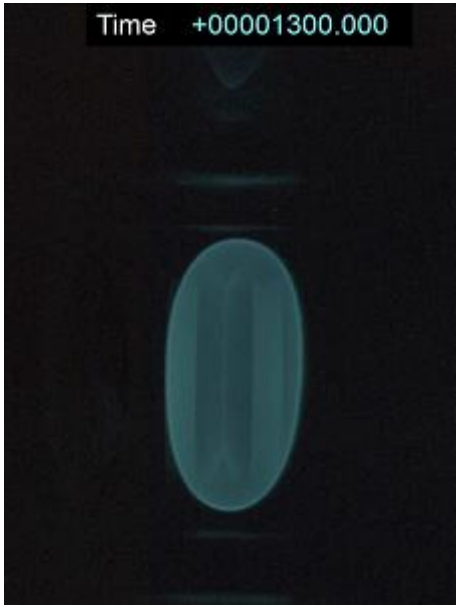


d = 24.7mm



→ Not ignited

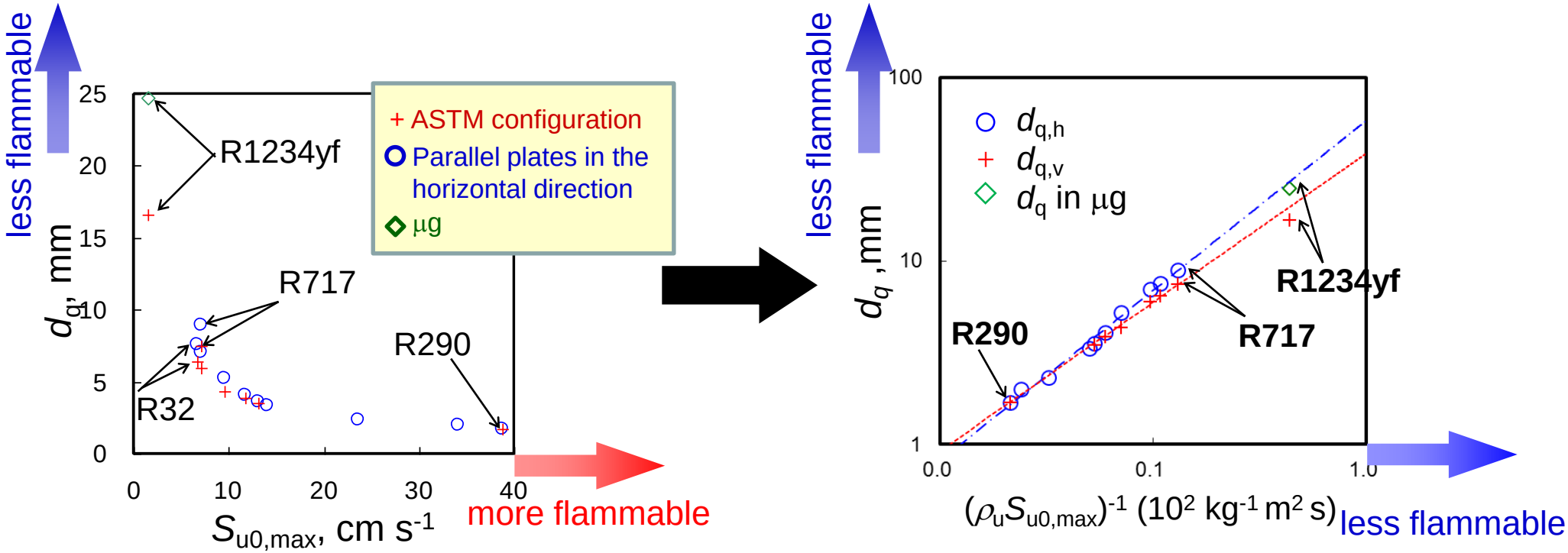
d = 24.9mm



→ Ignited

Results of QD

-Relationship between QD and BV-



- Obtained a single continuous function between d_q and S_u from highly to only mildly flammable compounds
- S_u <10 cm s^{-1} ⟺ d_q ≥5 mm

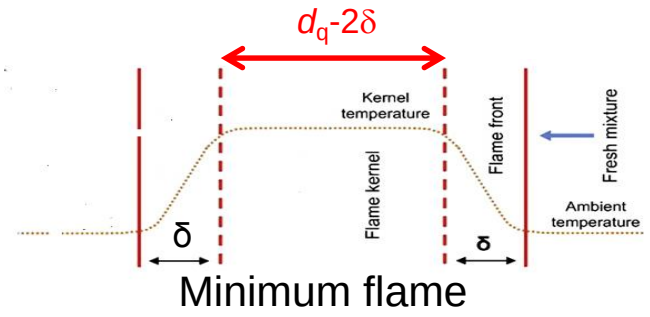
Estimation of MIE

Exp. values in this study

✓S_u, d_q

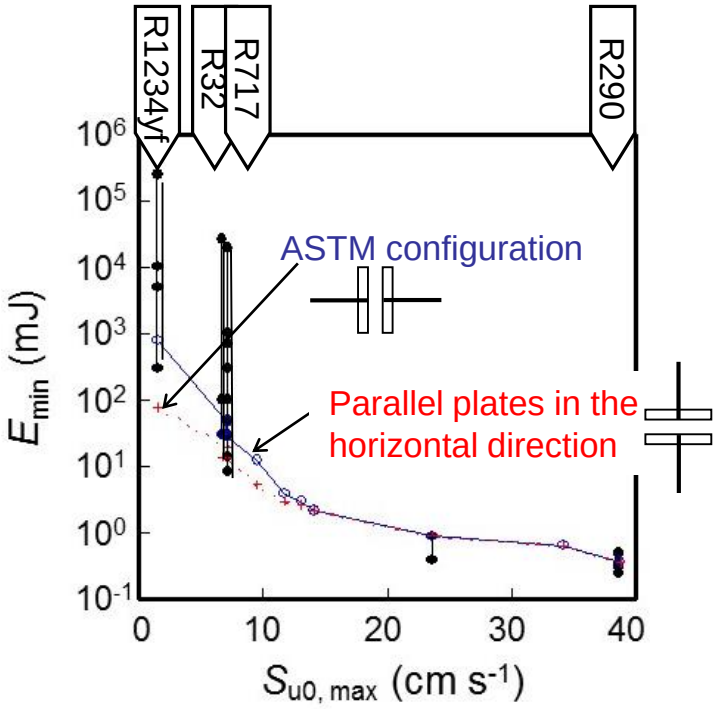
Theoretical eq. of E_{min}

This study: $E_{min} = (1/6)\pi (d_q - 2\delta)^3 \rho_b C_p (T_b - T_u)$



Minimum flame

Comparison between estimation and experiment



- Reported E_{min} are at most 3 orders of magnitude different
- Our estimation agreed with lower value of reported E_{min} for all the compounds without adding any modifications
- E_{min} was essentially proportional to the cube of d_q

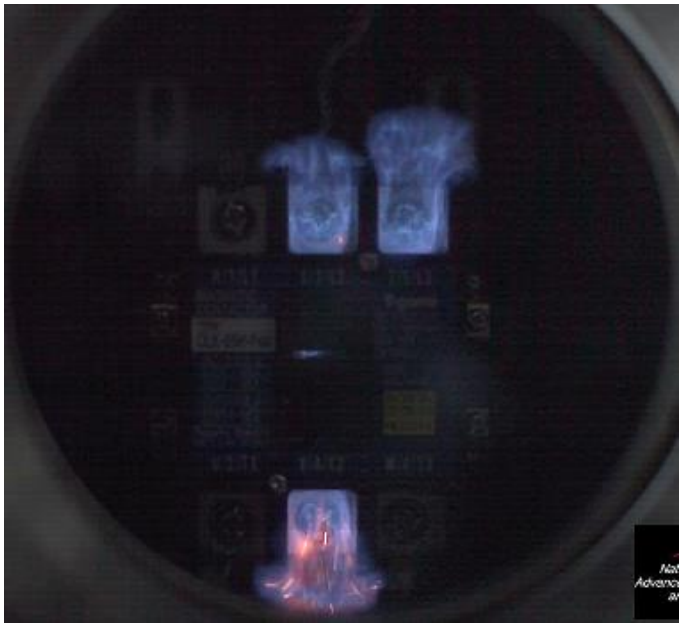
1. Background
 - Importance of evaluating low flammability

2. Fundamental flammability properties

3. MIE and quenching distance

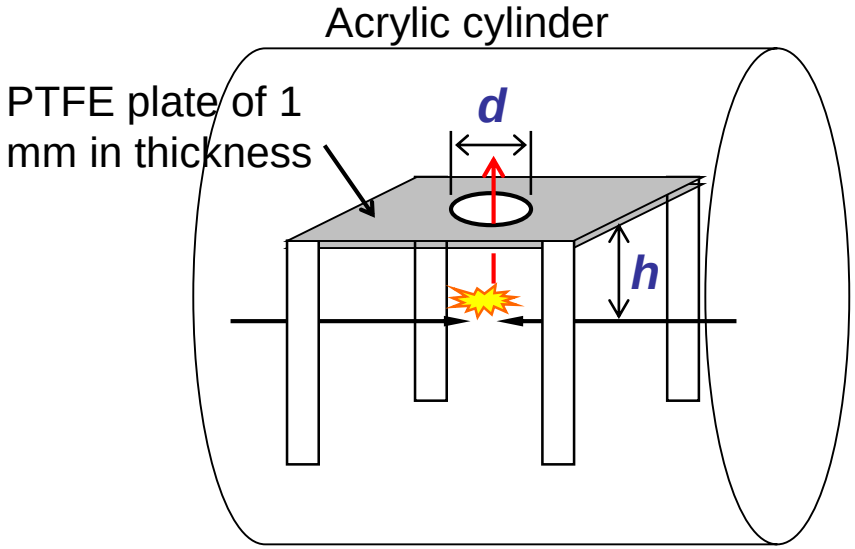
4. Flame extinction diameter
-Index of safe design of electric parts

5. Summary

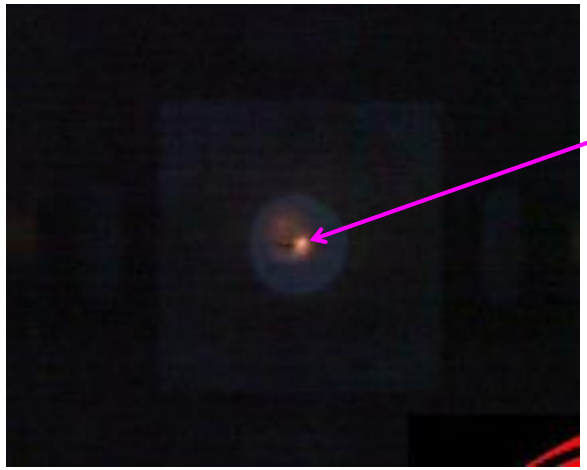


R152a flame goes out through opening of MC

Measurement of flame extinction diameter d^*

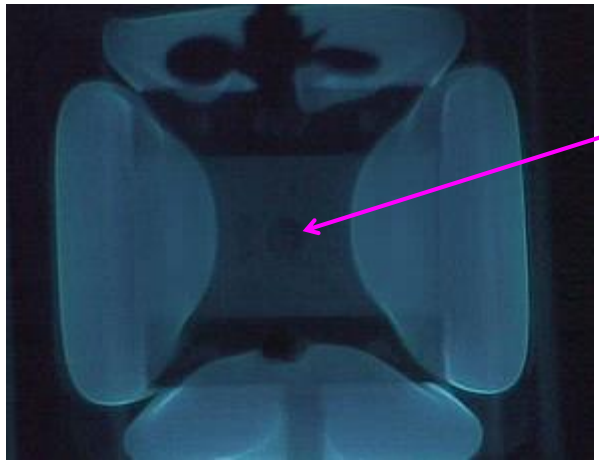


R290 (4.5%, *d* = 1.25mm)



"Go"

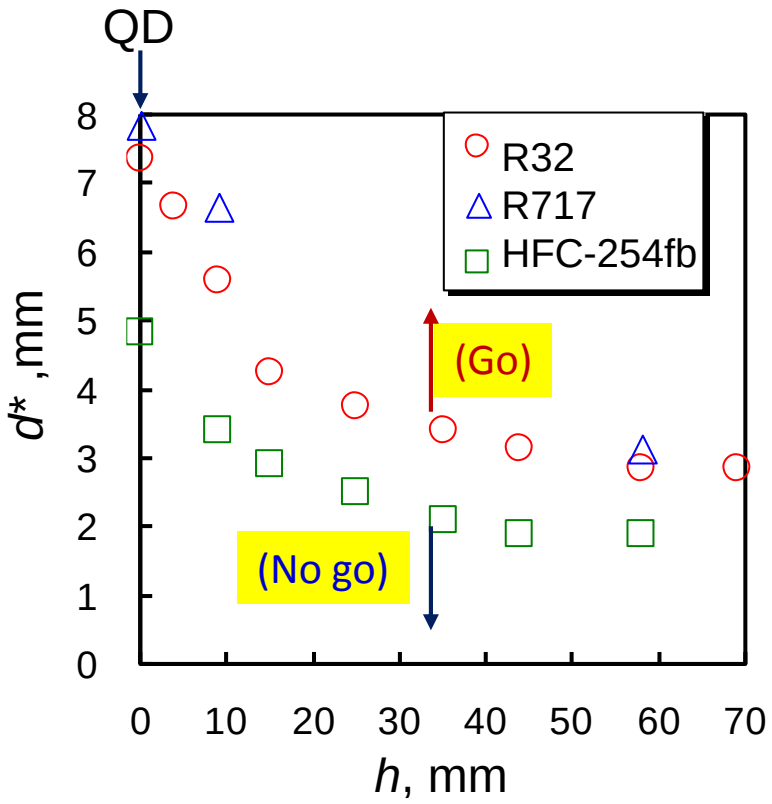
R1234yf, μg (9.4%, *d* = 10mm)



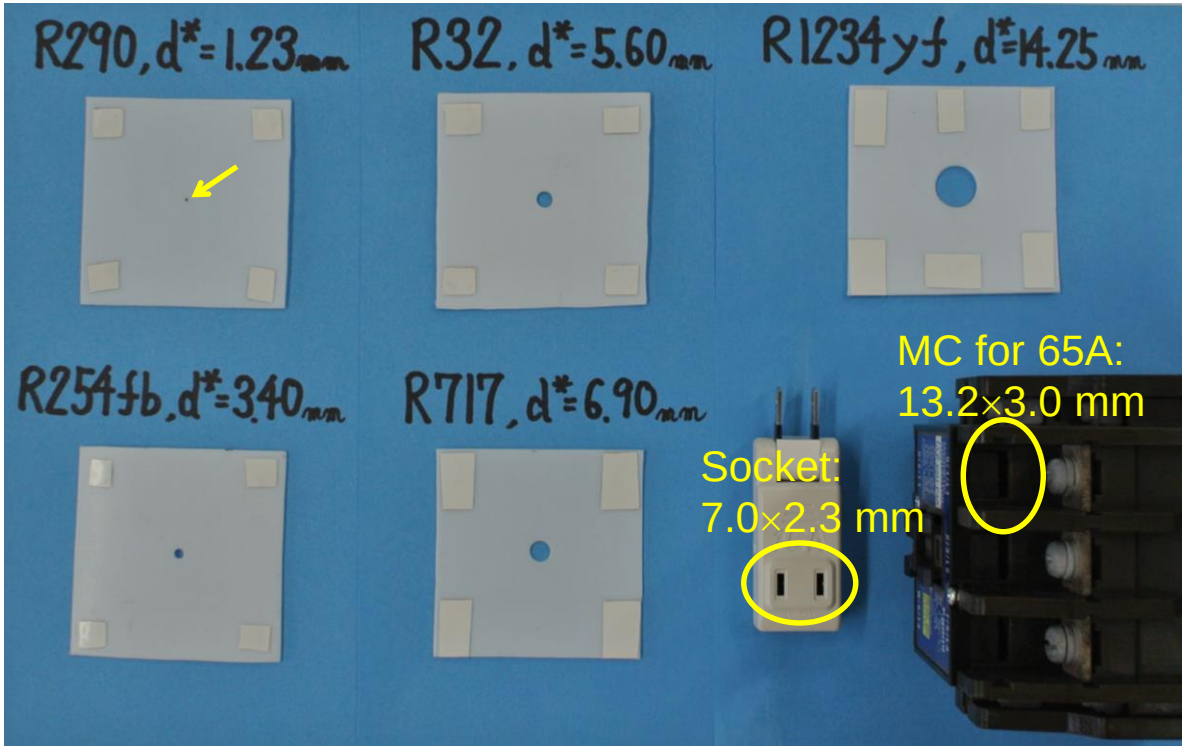
"No go"

Results of flame extinction diameter

d^* of 2L refs as a function of h



Comparison of d^* (@h = 9mm)



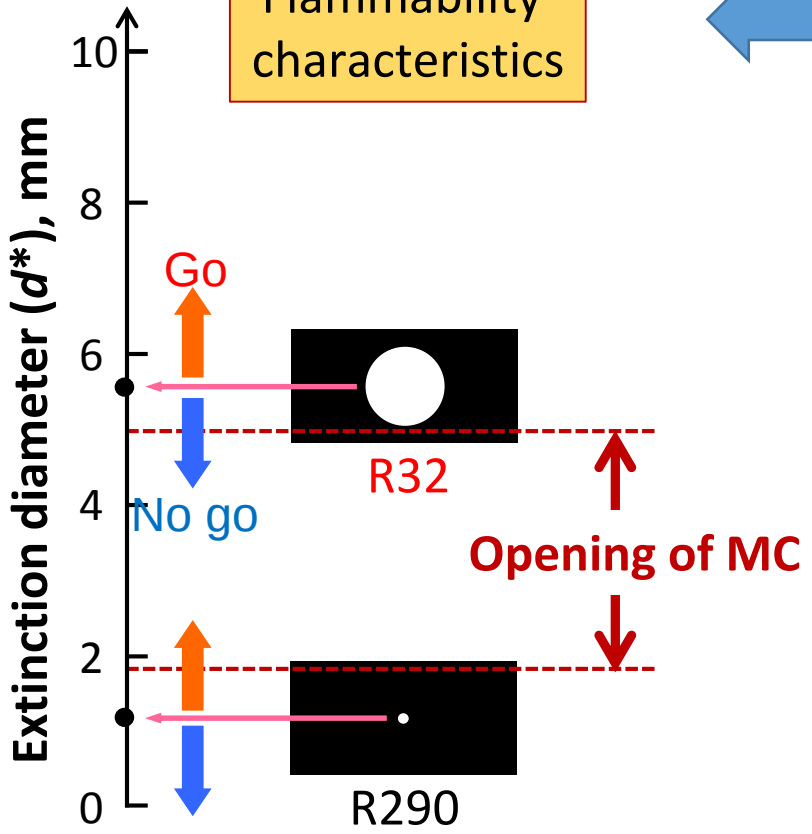
- R290 flame can pass the opening of socket
- R32 flame cannot pass the opening of MC

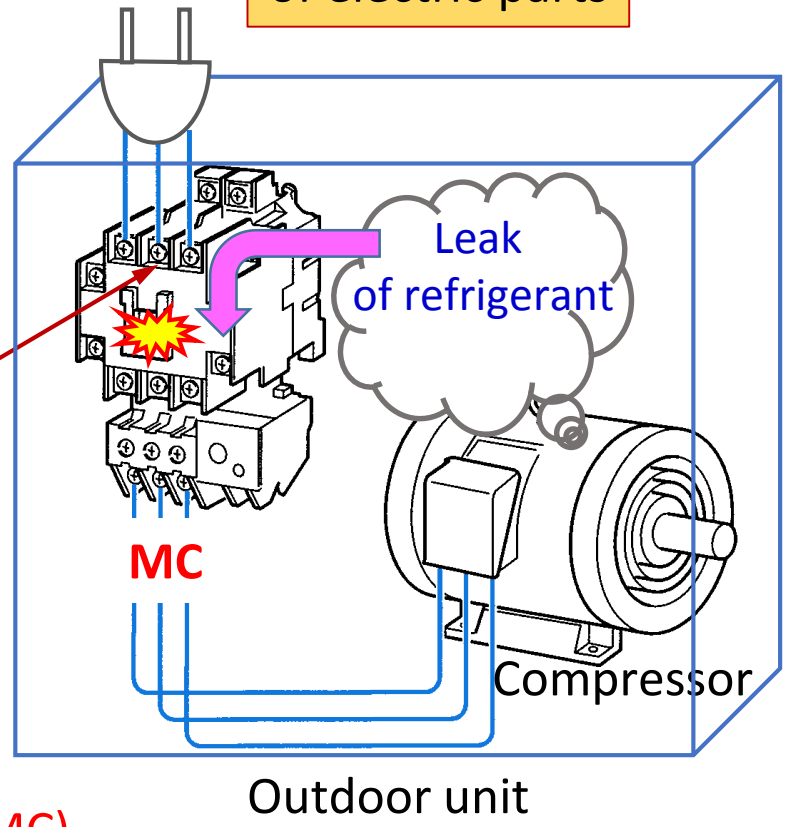
- d^* was positively related to d_q, negatively related to S_u
- With increasing h (growing flame sphere), d^* decreased and converged

Summary of part 4

Flammability characteristics

Structure of electric parts





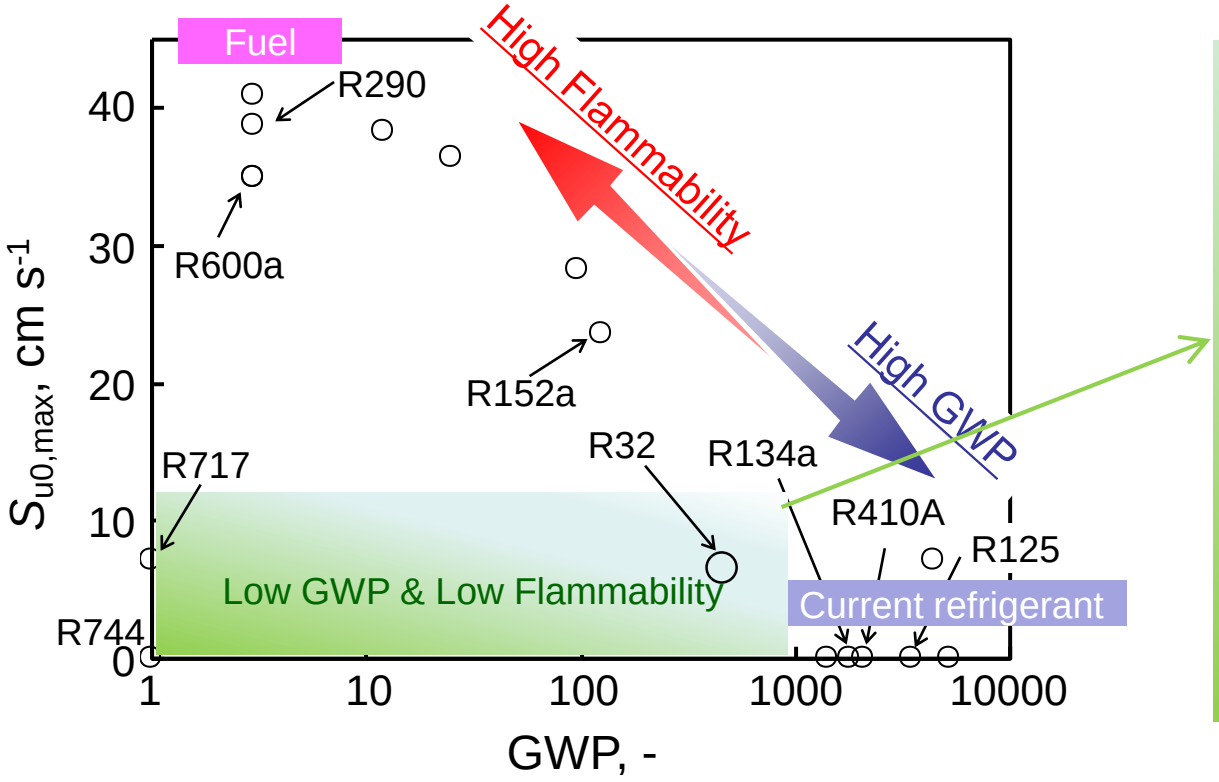
*d**(R32) > *D*(MC)

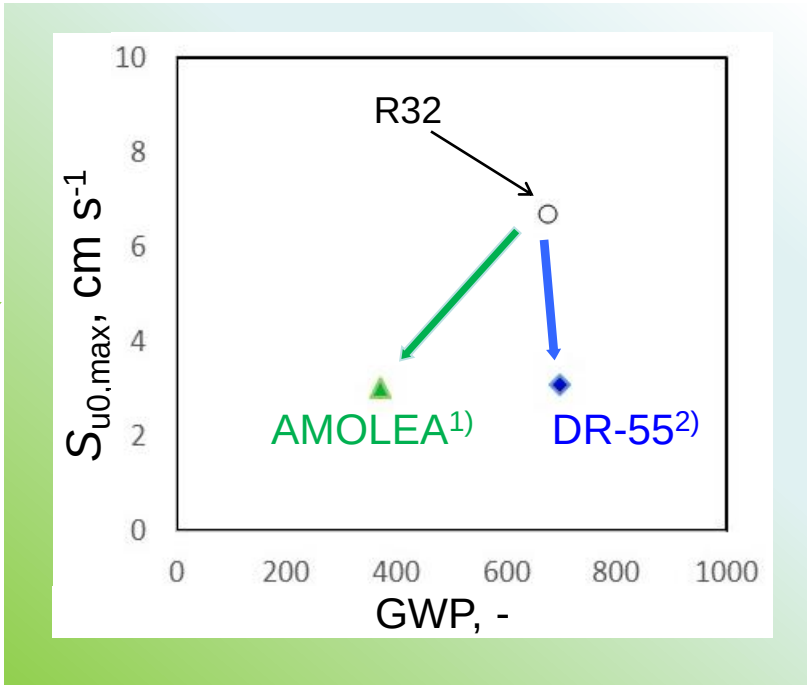
- Based on our experiment and theory, we can identify potential ignition sources of flammable refrigerants
  - -R290 flame having a high BV can pass the opening of socket
  - -2L flame having a low BV cannot pass the opening of MC

Summary

1. **Evaluation of low flammability** becomes practically important because the less flammable a material is, the more widely it will be accepted

   We are trying to develop evaluation methods and give the values to help development of good materials





1) AMOLEA: R1123/32 (45/55)
2) DR-55: R32/125/1234yf (67/7/26)

2. **In the NEDO project,** we studied ignition and extinction of refrigerants

- We measured QD for various compounds by various conditions and obtained a single correlation between S_u and d_q
- Based on this correlation, we estimated E_{min} as a starting point
- We will further study ignition and extinction characteristics applicable to practical risk assessment of 2L refrigerants

Thank you!