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ABSTRACT

An international drive toward sustainability of refrigeration systems will require the adoption of low global warming potential (GWP) refrigerants. Most of these are mildly flammable. Low-GWP refrigerants are generally well characterized in terms of their lower flammability limits, heats of combustion, and flame speeds. However, they are poorly understood in terms of their susceptibility to ignition from sources commonly encountered in residential and industrial settings, including motors, electric arcs, hot surfaces, and open flames. This important gap in understanding is the focus of this project. The primary objective is to perform tests to determine the viability of various ignition sources to ignite A2L refrigerants in air. Fifteen ignition sources were identified and tested. The A2L refrigerants tested were R-32, R-452B, R-1234yf, and R-1234ze. The tests were performed in a windowed stainless steel chamber with dimensions of 0.3 × 0.3 × 0.3 m and a volume of 27 L. Four of the ignition sources resulted in deflagrations or localized flames in the refrigerant-air mixtures. These were: hot wire (800 °C), safety match, lighter flame insertion, and leak impinging on candle, in order of decreasing ignition viability. Among the 15 potential ignition sources, it is remarkable that 11 were unable to ignite any of the mixtures considered here. These were: cigarette insertion, barbeque lighter, plug and receptacle, light switch, hand mixer, cordless drill, friction sparks, hair dryer, toaster, hot plate insertion, and space heater insertion. The inability of so many ignition sources to ignite A2L refrigerants is attributed here to the very long quenching distances of these refrigerants when mixed with air. Another remarkable finding is that these A2L refrigerants can act as either fuels or suppressants. For example, smoldering cigarettes were extinguished every time they encountered a stoichiometric mixture of A2L refrigerant and air.

1. INTRODUCTION

An international drive toward sustainability of refrigeration systems will require the adoption of low global warming potential (GWP) refrigerants. Most of these are mildly flammable, which has motivated extensive research (e.g., JSRAE, 2014; Linteris and Manion, 2015). Owing to concerns about fire safety, the first to be adopted may be A2L, or A1 but very close to the border with A2L. The A2L designation requires a lower flammability limit (LFL) above 3.5%, a heat of combustion below 19 kJ/g, and a laminar flame speed below 10 cm/s (ASHRAE 34, 2013).

Low-GWP refrigerants are generally well characterized in terms of their LFLs, heats of combustion, and flame speeds. However, they are poorly understood in terms of their susceptibility to ignition from sources commonly encountered in household and industrial settings, including motors, electric arcs, and other appliances.

The measurement of ignition limits suffers from some of the poorest repeatability in combustion research. The results can depend on seemingly negligible changes in the ignition source, the mixture conditions, or conditioning of the walls. Furthermore, absence of evidence is not evidence of absence. For example, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) has performed thousands of tests attempting to ignite gasoline vapors with cigarettes. None has ignited to date, but perhaps a future test will achieve ignition.

The minimum ignition energy (MIE) is known for some A2L refrigerants (ASTM E582, 2007; Takizawa et al., 2009; Minor et al., 2010). Ignition limits of refrigerants can be affected by chamber size and shape (Kataoka et al., 1996, Richard, 1998; Takahashi et al., 2003; Kul et al., 2004; Kul and Blaszkowski, 2007; Clodic and Riachi, 2009; Clodic and Jabbour, 2011).

A critical element in developing reliable risk assessments for A2L refrigerants is a detailed understanding of the required ignition source strength for the refrigerants. However, this understanding is weak. An improved understanding could improve refrigerant fault-tree analyses, such as that of Lewandowski (2012).

Potential ignition sources were identified by Goetzler et al. (1998), Goetzler and Burgos (2012), and Lewandowski (2012). Unfortunately, these studies either did not consider A2L refrigerants or did not consider or fully characterize the full array of ignition sources that can be expected in residential applications. Richard et al. (2012) considered hot-plate ignition of A2L refrigerants, but only below 700 °C. Boussouf et al. (2014) considered hot-plate ignition, but only for R-32.

This study measures the viability of potential ignition sources of A2L refrigerants. The refrigerants considered are R-32, R-452B, R-1234yf, and R-1234ze. For weak ignition sources, only stoichiometric mixtures are considered. For strong sources, lean mixtures are considered due to safety concerns. Full details of the tests are provided in Kim et al. (2017).

2. Experimental

The general schematic for the ignition testing is shown in Fig. 1. The chamber had dimensions of 0.3 × 0.3 × 0.3 m, with an internal volume of 27 L. Three of the sides and the bottom of the chamber were made of welded stainless steel. The front was clear acrylic for viewing. The top was open to allow access, but sealed with aluminum foil and tape to mitigate leakage and pressure rise during experiments. The chamber was air-tight when the top opening was sealed. The water bath was used to obtain steady flow rates and to flash the R-452b, which was extracted from the bottom of its container. After initial tests with a hot wire, a chimney was introduced on the top.

The experiments can be divided into two methods: premixed and diffusion. For the premixed method, refrigerant was then injected at a controlled rate until the desired concentration was reached after the ignition source was installed inside the enclosure. A fan was activated for 5 min to create a homogenous mixture and then the ignition source was energized. For the diffusion method, the ignition source was initially energized while the enclosure was filled with

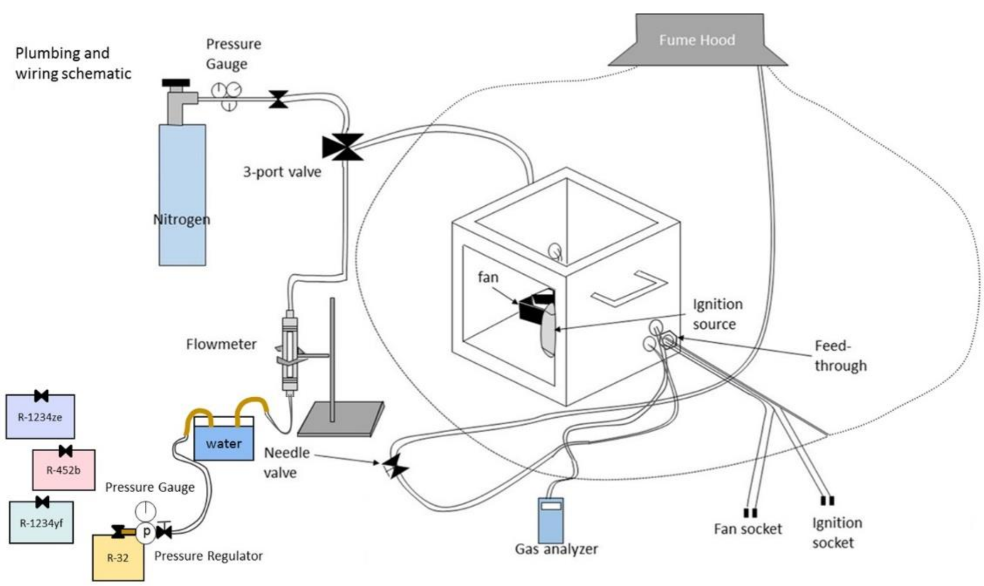

Figure 1: Test Schematic.

only air; refrigerant was introduced while the ignition source was already active. No fans were used for the diffusion method. The experiments were recorded by a video camera at 30 frames per second. After the experiments, the contents of the chamber were flushed with nitrogen gas.

Concentrations of the gaseous refrigerants in air were monitored by a portable gas detector. Relative humidity (RH) was measured by a humidity probe. Temperature and RH for the tests were 21–23 °C and 17–50%.

The refrigerant was introduced at a flow rate of 1 L/min. Assuming well-mixed conditions in the chamber, the refrigerant mole fraction as a function of time was found. This was confirmed with the gas analyzer. The gas analyzer and rotameter were calibrated. The flames observed here are described as either deflagrations of localized flames. Deflagration describes a flame that spreads in all directions to burn in nearly all areas of the chamber. Localized flame describes small blue flames that remain near and above the sources, but do not propagate outward or downward.

3. RESULTS

3.1 Hot Wire

A resistively heated Nickel-Chromium wire was tested. AC current was applied from a Variable AC controller (Variac). Table 1 summarizes the hot wire testing in quiescent conditions. In the initial tests, R-32 was released into the test chamber and then mixed by a fan. The voltage was increased slowly and steadily. To reduce the fire hazard, 8 – 10% R-32 (lower than the LFL of 14.4%) were used initially. No ignition was observed for these low concentration tests. Next, similar tests were repeated with mixtures containing 13 – 17% R-32. Deflagrations were seen when the voltage reached approximately 8 VAC. The flame propagated upward from the hot wire until reaching the top of the chamber and then downward.

R-32 was also released into the chamber using a diffusion method whereby the wire was heated to its steady state temperature at 8 VAC and then refrigerant was introduced. The fan was not activated. Ignition was observed with a blue localized flame as shown in Fig. 2. After a few seconds of flame propagation, the flow of refrigerants was terminated and the flame was extinguished with nitrogen gas.

R-1234ze and R-452B were tested, and deflagrations were observed for both. Premixed tests were repeated for all four flammable refrigerants at stoichiometric conditions. The flame propagation behavior at stoichiometric conditions was consistent with the previous round of premixed experiments, as illustrated in Fig. 3. Also, the flame speed of R-32 was faster than R-1234yf and R-1234ze, but slower than R-452b. All four refrigerants were ignited by the wire around 9 V. The laminar flame speeds of all these refrigerants are below 10 cm/s (Papas et al., 2017).

Table 1: Hot wire results.

Refrigerant	Mole fraction	Method	Wire Temperature, °C	Ignition
R-32	0.078	Premixed	863 – 1140	No
	0.096	Premixed	863 – 1140	No
	0.100	Premixed	863 – 1140	No
	0.130	Premixed	788	Deflagration
	0.170 – 0.174	Premixed	700 – 863	Deflagration
	0.115	Diffusion	788	Localized flame
R-1234yf	0.078 – 0.080	Premixed	788 – 921	Deflagration
R-1234ze	0.065 – 0.078	Premixed	788 – 921	Deflagration
R-452B	0.145 – 0.147	Premixed	788 – 911	Deflagration

Figure 2: Hot wire in R-32 for the diffusion method. The flammability limit is estimated at 3.8% concentration.

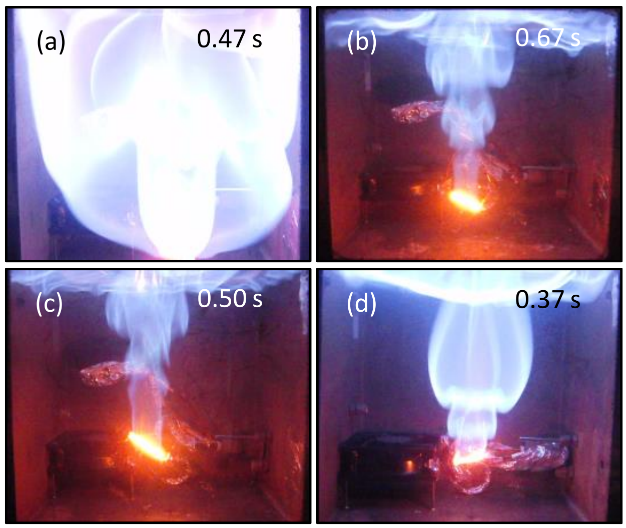

Figure 3: Deflagrations seen from slow voltage increase of hot wire in stoichiometric mixtures: (a) R-32; (b) R-1234yf; (c) R-1234ze; and (d) R-452b. Images taken when the propagating flames hit sides of the walls.

3.2 Safety Match

A wooden safety match was sealed inside the chamber and the match head was wrapped with a Nickel-Chromium wire for ignition. The energy supplied to the wire was controlled by a variable AC controller (Variac). Care was taken to ensure that the hot wire ignited the safety match and not the mixture itself; with such a small wire length, a low voltage level, and a short duration, the hot wire alone would not have been able to ignite the mixture. All refrigerants were ignited by the safety match as pictured in Fig. 4. A localized flame was observed in R-1234yf. For R-32, R-452B, and R-1234ze, deflagrations were observed where the flames propagated upwards from the safety match and then gently downward after reaching the top of the chamber.

3.3 Lighter Flame Insertion

A barbeque lighter was tested in stoichiometric mixtures of refrigerant and air. The barbeque lighter was ignited in air outside the chamber and then inserted into the chamber. As shown in Fig. 5, a localized flame was observed in R-1234yf, R-452B, and R-1234ze. A deflagration was observed in R-32, where the flames propagated upwards from the lighter and then gently downward after reaching the top of the chamber.

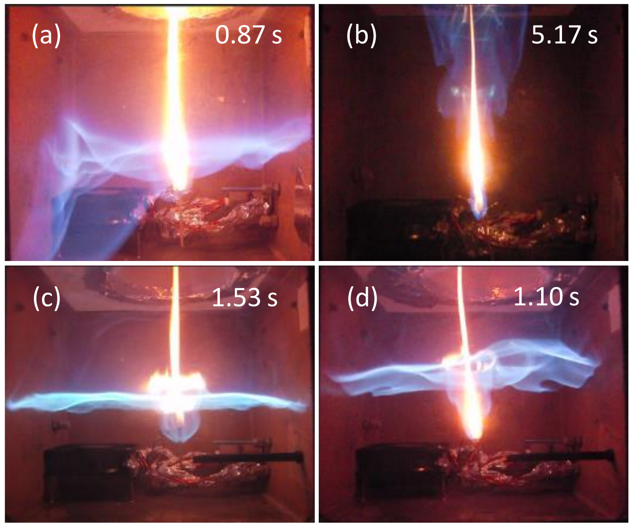

Figure 4: Safety match tests: (a) R-32: 17% (LFL = 14.4%), (b) R-1234yf: 7.2% (LFL = 6.2%), (c) R-1234ze: 9.8% (LFL = 6.5%), and (d) R-452B: 15.5% (LFL = 11.9%).

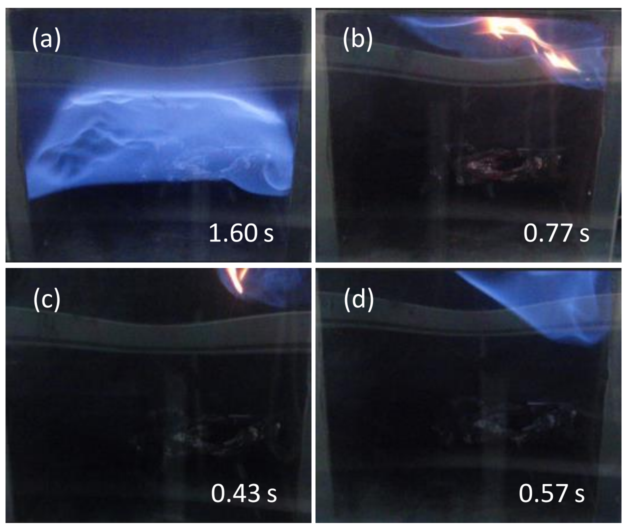

Figure 5: Lighter flame insertion results for (a) R-32: 16%, (b) R-1234yf: 8%, (c) R-1234ze: 7.5%, and (d) R-452B: 13%. The largest flames are shown.

3.4 Leak Impinging on Candle

Refrigerants were released into the chamber from one of two different locations, a high and low leak, while a candle was burning. The first test series featured R-32 at the lower leak location. Long candles (150 mm high) were used. No localized flames or deflagration flames were observed. The candle flame location was higher than leak location. It can be assumed that the refrigerant did not fully diffuse up to the candle without any fan activation. Thus, short candles (50 mm high) were used and the candles were lower than refrigerant leak location. Interestingly, localized blue flames were seen around the short candles, as pictured in Fig. 6, prior to the candle being extinguished. Mole fractions were 0.035 – 0.053 which correspond to 62 – 97 s of extinction time. No deflagrations were observed in this configuration. The candle extinguished around 4.6% - 7.3% of R-32, as estimated from the leak rate and duration. The mixture was not homogeneous, so this concentration is approximate.

A second series of tests with R-32 were conducted. Short candles (15 mm wick, 50 mm high) were used. R-32 was released into the chamber from the upper inlet while the candle was already burning. The candle was located in the center for the first three experiments. No ignition was observed and the candle flame was extinguished at 111-156 s. Next, the candle location was varied to confirm this result at various locations. No localized flames or deflagrations

Figure 6: From lower leak testing, the candle extinguishes at 4.7% R-32. A blue localized flame is visible.

were observed in upper leak candle testing. There was no effect of candle location in the small box.

Next, both high leak and low leak experiments were conducted in R-1234yf with the test conditions indicated in Table 2. The R-1234yf was released into the chamber while the candle was already burning. Short candles (50 mm high) and long candles (over 150 mm high) were used at the center location of the chamber.

As shown in Fig. 7a and Fig. 7b, blue localized flames were observed prior to extinction. The localized flames appeared larger than the previous localized flames from R-32. The candle was extinguished by R-1234yf at approximately 3.6 - 6.4%. Again, oxygen vitiation and turbulence extinction were ruled out.

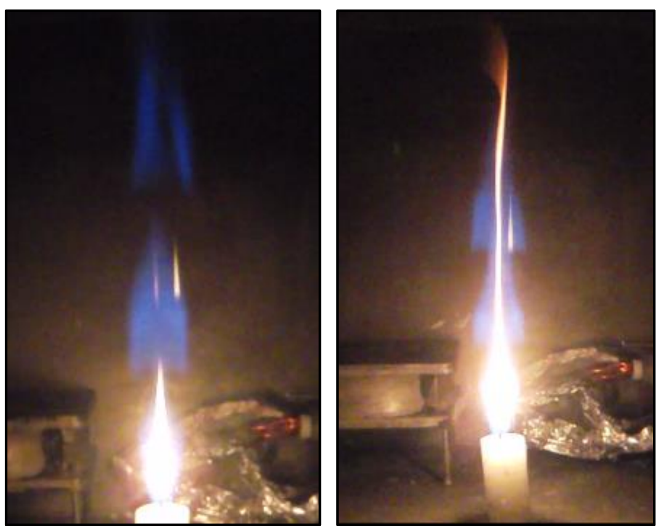

Figure 7: Candle tests in R-1234yf: (a) Upper leak with approximately 4% R-1234yf; (b) Lower leak with approximately 3% R-1234yf.

Table 2: Candle testing of R-1234yf results, with the candle in the center location. In all cases the ignition was localized.

Leak location	Mole fraction	Extinction Time (s)
Upper	0.054	80
	0.064	119
Lower	0.036	65

Lower leak tests of R-1234ze and R-452B were conducted. Short candles (50 mm high) were used at the center location. For R-1234ze, a blue localized flame was observed, but no flames were observed during R-452B tests prior to extinguishment of the candle flame.

3.5 Cigarette Insertion

Before testing the ignition potential of a cigarette, the temperature of a smoldering cigarette was measured by a bare thermocouple wire. The maximum temperature was 490 °C. Cigarette testing was conducted with two different methods. In the first method, a cigarette was installed inside the chamber. The cigarette tip was connected to a Nickel-Chromium wire. The energy supplied to the wire was controlled by a variable AC controller. Caution was taken to ignite only the cigarette and not entire the mixture with the wire.

R-32 was tested through the first method. Mole fractions were 0.170–0.180. R-32 extinguished the cigarette within 10 min in each case. Re-ignition of the cigarette was attempted with the hot wire, but failed on each attempt.

The second method involved inserting a lit cigarette into the chamber of premixed refrigerant. All four refrigerants were tested, with at least four attempted cigarette insertions each. Conditions were stoichiometric. All four refrigerants extinguished the cigarette within 100 s. Oxygen depletion was ruled out because with the vessel filled with air cigarettes were observed to burn to completion, about 16 min.

3.6 Barbeque Lighter

The nozzle of a butane lighter was sealed inside the chamber with the trigger activated by an electrical actuator. Testing involved three methods. In the first method, R-32 was released into the chamber while the barbeque lighter was burning. In the second method, premixed conditions were prepared inside the chamber, followed by activating the butane lighter. The lighter was able to sustain a butane flame in 0%, and 2%, but not at 3% R-32. For the third method, the chamber was filled with a stoichiometric mixture and the lighter was sparked with butane flowing. Spark ignition was attempted at least 10 times.

For the diffusion testing, the barbeque lighter could not ignite above a concentration of 3.8% R-32 in air. It was extinguished at 68 s. For the second method, no refrigerant ignition was observed. Oxygen vitiation and turbulence extinction were ruled out. With the third method, all four refrigerants were tested for nearly stoichiometric conditions. The butane lighter did not ignite the mixture and only sparks were seen without any flame from all four refrigerants at stoichiometric conditions.

3.7 Other Nonviable Ignition Sources

Other ignition sources were tested including: as plug and receptacle under load, light switch under load, hand mixer, cordless drill, friction sparks, hair dryer, toaster, hot plate, and space heater. All these sources have peak temperatures well in excess of the AITs of these refrigerants. Even with stoichiometric conditions, no ignitions were observed.

An apparatus was prepared to insert and remove a plug from a receptacle. A 3 A and 12 VDC actuator was loaded in the test chamber to insert and remove the plug. The receptacle was connected to a power supply and a 2240 W vacuum cleaner acted as the load on the plug; the vacuum cleaner was located outside of the chamber. No ignitions were observed.

A light switch creates an arc each time it opens or closes under load. It was placed in the windowed chamber. This switch is rated for 15 A, 120 VAC. Also, a 3 A and 12 VDC actuator was placed in the test chamber to operate the switch in both directions. The load on the light switch was a 2240 W vacuum cleaner outside of the chamber. The sparks were seen clearly. The light switch was turned on and off for at least 20 cycles for each refrigerant. No ignitions were observed.

A hand mixer, with a maximum power of 200 W, was used as a potential ignition source. This mixer had an excitation of 110 VAC and dimensions of $0.21 \times 0.15 \times 0.11$ m. Continuous blue sparks were visible from the motor. It was activated for at least 100 s. No ignitions were observed.

Tests were performed with a 380 W, 18 VDC cordless drill, which has a brushed motor. Excitation was with a battery outside the chamber, for which the voltage was measured to be 18.5 V at maximum drill speed. The drill was loaded into the chamber and the top vent was sealed with a chimney. Continuous blue sparks were clearly visible from the brushed motor. Each refrigerant was tested for at least 120 s. No ignitions were observed.

For friction spark testing, a grinding stone with a cordless drill and a ferrocerium flint rod were prepared. Temperatures of 3000 °C can be reached (Wikipedia). The stone was placed against the flint in the windowed chamber. A switch was installed outside of the chamber to operate the cordless drill. When the switch was turned on, continuous friction sparks (2-3 cm) were generated for at least 1 min. No ignitions were observed.

A hair dryer (1600 W, 110 VAC) was observed. It had dimensions of 0.08 × 0.11 × 0.19 m. The coil temperature in open air was measured by a bare Type-K thermocouple. The steady temperature reached around 200 °C. The time constant was found to be 5.12 s. The hair dryer was operated for at least 45 s at full power. No ignitions were observed.

A toaster was tested, namely a 2-slice toaster with dimensions of 0.2 × 0.25 × 18 m. The coil temperatures in air were measured by a bare and a shielded thermocouple. The temperature of the coil increased rapidly and the maximum temperature measurement was 500 °C. This is higher than the autoignition temperatures of R-1234yf (405 - 420°C) and R-1234ze (368°C) reported by Honeywell. The toaster was operated for at least 100 s. No ignitions were observed.

A hot plate was prepared. The hot plate excitation was 750 W and 120 VAC. The heating element temperature was measured with a thermocouple and the highest temperature observed was 541 °C. If the hot plate were left to heat inside the sealed test chamber, there was a risk of melting the acrylic window. Furthermore, a hot enclosure increases the likelihood of a dangerous explosion if ignition occurred. This posed a safety risk so an alternate test method was created. The hot plate was connected to a pulley to allow it to lower safely down into the center of the windowed chamber after it reached steady state temperature and stoichiometric conditions were established inside the chamber. The hot plate was inverted and turned on at full power for 10 minutes to reach steady state temperature of its heating element. It faced downward. Then, the aluminum foil cover was cut open by a razor blade to minimize the possibility of the refrigerant leaking from the space. Finally, the hot plate was inserted into the chamber using the pulley. No ignitions were observed.

A ceramic tower heater, with a maximum power of 1500 W, was tested. The heater (0.58 m tall) was too tall to put inside the 27 L windowed chamber. Accordingly, tests were conducted with the insertion method, similar to the hot plate experiments. The heater was prepared separately. Then it was turned on for at least 10 minutes so its fins reached steady state temperature (100 °C). No ignitions were observed.

3.8 Results Summary

A total of 15 potential ignition sources were used for R-32, R-1234yf, R-1234ze, and R-452b refrigerants, generally mixed stoichiometrically with air. The overall test matrix and the results summary are shown in Table 3.

Table 3: Test matrix and result summary (D: Deflagration, L: Localized flame, and N: No ignition).

	R-32	R-452B	R-1234yf	R-1234ze
Hot wire	D	D	D	D
Safety match	D	D	L	D
Lighter flame insertion	D	L	L	L
Leak impinging on candle	L	N	L	L
Cigarette insertion Barbeque lighter Plug and receptacle Light switch Hand mixer Cordless drill Friction sparks Hair dryer Toaster Hot plate insertion Space heater insertion	N	N	N	N

4. CONCLUSIONS

The key findings of this study are as follows.

- The inability of so many ignition sources to ignite A2L refrigerants is attributed here to the very long quenching distances of these refrigerants when mixed with air. These distances are difficult to measure reliably for A2L refrigerants but are on the order of 8 – 25 mm. Although these 11 nonviable ignition sources have high temperatures, their high temperature regions are too close to walls to support combustion.
- A2L refrigerants were observed to act as either fuels or suppressants. For a strong ignition source like a resistively heat hot wire, they act as fuels. Conversely, smoldering cigarettes were extinguished every time they encountered a stoichiometric mixture of refrigerant and air. The barbeque lighter spark was unable to ignite either the lighter's butane or the surrounding stoichiometric refrigerant mixtures. Candle flames also were extinguished when refrigerants impinged on them, although for a brief time they caused localized burning of refrigerant.
- Among the four refrigerants, the hot wire testing indicated R-452b had the fastest flame speed whereas R-1234yf had the slowest. For safety match tests only R-1234yf had no deflagrations. During candle tests the blue localized flames from R-1234yf and R-1234ze were much larger than those from R-32, and none were observed with R-452B.

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