COMMENT ON EPA PROPOSED RULE

OFFICE OF AIR and RADIATION

PROPOSED SIGNIFICANT NEW ALTERNATIVES POLICY (SNAP)

Protection of Stratospheric Ozone: Listing of Substitutes for Ozone-Depleting Substances – Hydrocarbon Refrigerants

EPA-HQ-OAR-2009-0286; FRL-9147-9

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BY

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I. Introduction, Background, & Summary

Honeywell International Inc. ("Honeywell") is a leading innovator in the development of refrigerants and blowing agents. Our Fluorine Products business is a global supplier of these products to the appliance and HVAC industries. We operate a dedicated, world-class technology and research facility in Buffalo, New York that focuses on the development and testing of new refrigerants and blowing agents. Honeywell scientists in Buffalo possess extensive experience in refrigerant safety and testing.

In the United States, since the mid-nineties, all refrigerators have used the refrigerant HFC-134a. This product is safe, non-toxic, and non-flammable. We are not aware of any significant safety incidents involving HFC-134a. Some manufacturers in other countries have switched to hydrocarbons (HCs) in stationary refrigeration applications. While certain HCs, such as isobutane, exhibit good performance as refrigerants, these products are <u>*highly flammable and explosive even in small amounts*</u>. Several companies have now requested that EPA approve the use of HCs in refrigerators sold in the U.S. We are submitting this written comment to express our concerns and to provide EPA with the results of our own experiment performed by our scientists in Buffalo that we believe warrants additional consideration and assessment by EPA.

A. Honeywell's experiment lends credence to past reports of safety concerns with isobutane refrigerators.

In 2009, a major consumer refrigerator manufacturer announced a global recall of isobutane refrigerators as a result of safety incidents that occurred in Asia and Europe. It should be noted these incidents occurred despite the fact that these units were specifically designed to operate with isobutane, and were designed to eliminate potential ignition sources. The electrical insulation in the defrost mechanism in these units carbonized, leading to partial short-circuiting and sparking. The sparking corroded the adjacent tubing which resulted in a leak of HC refrigerant. Isobutane concentrations accumulated enough to exceed the lower flammability limit (LFL) in the closed refrigerator unit. During the next defrost cycle, the faulty electrical circuit resulted in ignition of the refrigerant and an explosion.

Honeywell performed its own experiment, described in more detail below, that illustrates the risks of using HCs in U.S. refrigerators. Our study found that a leak in a refrigerator using isobutane refrigerant can result in concentrations of isobutane above the LFL inside and outside the refrigerator compartment. Because isobutane need only come into contact with 0.25mJ of energy to ignite, even static sparks (5-15mJ) can cause ignition resulting in serious damage where concentrations of isobutane exceed the LFL, as shown in the Honeywell study.

B. EPA's risk assessment does not address all the risks from isobutane refrigerators.

The ICF Risk Screens included in the EPA docket do not fully address the risks of using isobutane in refrigerators for three reasons. First, the ICF assessment assumes that external leaks of isobutane never exceed the LFL. Second, ICF under- estimates the possible sources of ignition of internal isobutane leaks. Third, ICF does not address two other leak and ignition possibilities, including the scenario that occurred in the recalled hydrocarbon refrigerators.

Honeywell recently performed its own assessment. We measured refrigerant leak concentrations inside and outside the refrigerator, assembled a fault tree analysis, and conducted a test to analyze the risk associated with isobutane.

Honeywell measured refrigerant charge leak concentrations using the procedure outlined in UL Standard 250 which resulted in a leak quantity of 55 g. Inside the refrigerator freezer compartment, Honeywell measured concentrations of isobutane at 3.2% which is above the LFL for isobutane of 1.8%. Outside the refrigerator cabin, Honeywell measured concentrations of isobutane exceeding the LFL in all five sampled locations of a kitchen mockup.

We then developed a fault tree analysis based on a review of the failure modes (i.e. leak potential) and likely event frequency. Our analysis indicates that the frequency of ignition events in a refrigerator using isobutane exceeds the levels identified in the AD Little risk assessment report.

Honeywell also conducted a test by leaking 80% of the isobutane charge into the inlet of the evaporator of a typical U.S. refrigerator, according to UL Standard 250. A spark was generated to simulate a faulty defrost heater connection in the freezer compartment, the spark was sufficient to ignite the leaked refrigerant and the resulting deflagration blew the doors off of the unit and threw the freezer door 48 feet.

Based on these assessments and the shortcomings of the ICF Risk Screens, Honeywell is concerned that the EPA has potentially under-estimated the safety risks associated with use of HC refrigerants.

C. Honeywell encourages EPA to complete a critical evaluation of the existing HC refrigerator risk assessments prior to approving use of HCs in this application.

EPA should conduct additional risk assessments before determining to allow the use of hydrocarbon refrigerants, which have the potential to create greater risk to the public than existing refrigerants or other less flammable options.

II. Fault Tree Analysis for Refrigerator/Small Appliance Leak Incidents Show the Risk of Flammability When Using HCs In Refrigerators.

A. Refrigerator Failure Due to Leakage of Refrigerant

There are two primary reasons to repair a refrigerator: either the compressor has failed and is replaced or a leak has developed on a connection. We assume that the majority of service calls are related to compressor failure with a lesser percentage of joint leaks and evaporator corrosion failure. Our estimate is that 5% of repairs are due to joint leakage, 1% are related to evaporator corrosion and the balance of repairs are due to compressor failure. Vibration metal fatigue, line rubbing, and liquid line routing to avoid door sweating failures are rare now, and our service shop indicated that they do not repair those units due to high labor costs.

Current leaks of 134a do not raise serious safety concerns, but leaks of isobutane or other HCs could be a serious safety risk. EPA's proposed rule does not include requirements to reduce refrigerant leak rates for refrigerators manufactured to use HCs. Thus, we can assume that the leak rates for 134a will be similar to those likely to occur with HC refrigerants.

Based on our own internal estimates, we assume that 100,000 lbs of R134a per year are sold to service household refrigerators and other small appliances. An average refrigerator now requires about 5 oz of refrigerant and we estimate that an additional 3 oz are wasted for leak checking, improper overcharge or other service-related activities (this allows for a conservative estimate of the number of units serviced) for a total of 8 oz of refrigerant (0.5 lbs) per refrigerator for an average of 200,000 units repaired each year. Leaks occurring after about 10 to 12 years are deemed to be end of life (EOL), leaks occurring during warranty and before EOL are likely to be field serviced if the leak is easily identified and accessible. We estimate that only 1% of refrigerators are field serviced annually due to refrigerant leakage (or a ratio of 100 EOL/repaired refrigerators), resulting in approximately 2,000,000 refrigerator refrigerant system failures due to leakage of refrigerant each year in the US

To conduct this risk assessment, typical refrigerators were surveyed to determine the number of brazed joint connections. We found these refrigerators averaged 8 individual joints per unit with 2 joints servicing the evaporator interior to the unit. In the past, the brazed junction between the copper line and an aluminum evaporator represented a source of galvanic corrosion leakage (leakage due to electrical potential between two dissimilar metals); however, we feel that problems with dissimilar metal joining at the heat exchangers have largely been corrected at this time and the probability of these joints is now equal to the other brazed joints in a system. Evaporator corrosion typically represents an end of life event and is the result of ice, water and contaminates corroding or fatiguing the evaporator metal over the life of the unit.

In order to perform a fault tree analysis, the above analysis indicates the frequency of refrigerant leakage occurring internal to the cabinet:

$$200,000\,\frac{\text{Refr. repairs}}{\text{year}}*\left(5\%\text{ leak failures}*\frac{2\text{ internal joints}}{8\text{ total joints}}+1\%\text{ evap corrosion failures}\right)*100\,\frac{\text{EOL}}{\text{repair}}=260,000\,\frac{\text{internal leak failures}}{\text{year}}$$

The frequency of refrigerant leakage occurring external to the cabinet becomes:

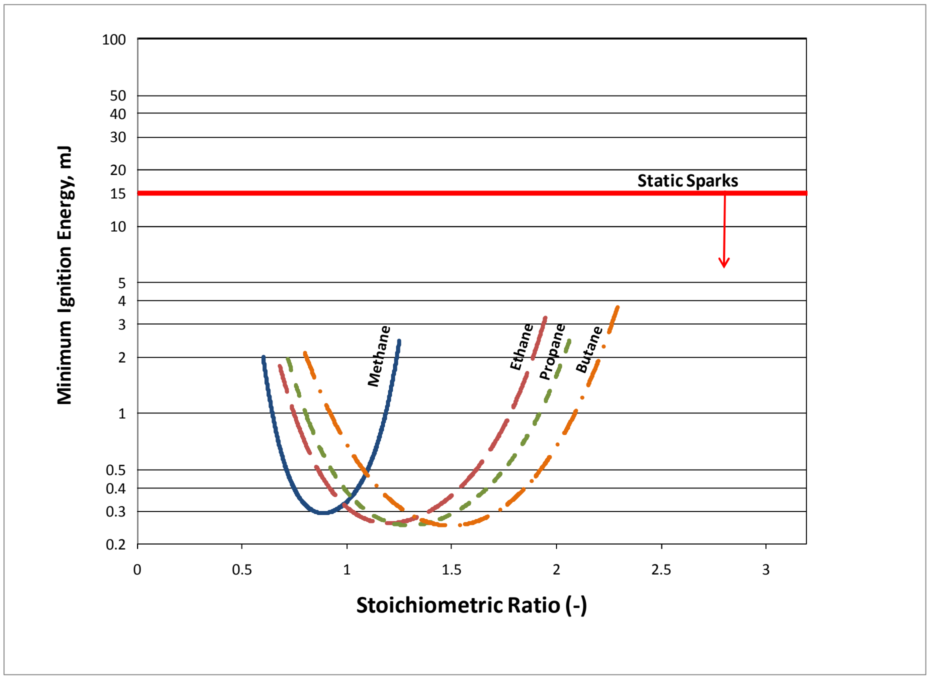
$$200,000\,\frac{\text{Refr. repairs}}{\text{year}}*\left(5\%\text{ leak failures}*\frac{6\text{ external joints}}{8\text{ total joints}}\right)*100\,\frac{\text{EOL}}{\text{repair}}=750,000\,\frac{\text{external leak failures}}{\text{year}}$$

To determine the failure rate due to refrigerant leakage, we examined the total existing refrigerator market and likely growth in the market. DOE[1] estimates that in 2008, 26% of households had multiple refrigerators and that this rate increases about 1% each year. The total installed base is 145 million standard-sized refrigerators with 7.5 or more cubic feet with an annual production rate of approximately 10 million units.

B. Ignition Events

Isobutane can be ignited with as little as 0.25mJ of energy, as shown below. Much higher energy levels are generated in all electrical device faults in a refrigerator. Appliances designed for isobutane have switches and other ignition sources such as thermostats placed inside the cabinet which have the potential to spark and cause an ignition during a leak event. Also, there is the possibility that faulty electrical connections for components such as the defrost heater could produce sparks that ignite leaked isobutane (demonstrated in Appendix A).

[1] http://www.energystar.gov/ia/partners/manuf_res/downloads/Refrigerator_Market_Profile_2009.pdf



Minimum Ignition Energies for light hydrocarbons. Lewis and Von Elbe, 1961

Small energy amounts such as electrostatic discharges can ignite isobutane. In fact, human-generated sparks generate 5 to 15 mJ, more than enough to ignite isobutane (John Bond, 1991).

1. Sparks and Auxiliary Components (lights, switches, etc.)

Lights, Fans, Switches, controls and all electrical devices (the defrost heater is treated separately below) in each refrigerator can produce an electrical spark sufficient to ignite leaked refrigerant. We would expect equipment manufactures to produce units at a six sigma quality levels which would result in a failure rate of one refrigerator in a million per year that will have a sparking event due to some light contact, fan, or switch contact. An electrical spark from any of these components, would have enough energy to ignite leaked refrigerant. The minimum ignition energy of hydrocarbons is less than 3 mJ in the flammable region.

2. Static Sparks – Owner/Resident or Plastic Rubbing

Precautions may be warranted on door openings that could cause a static discharge between a person reaching into a refrigerator or between the rubbing of non electrically conductive plastic parts (doors, hinges, fan blades or other plastic parts). Our estimation is that failures in this mode are on the order of 10 ppm (10 refrigerators per million per year) because currently there is no reason to protect against static discharge and 6 sigma design practices have not been needed for R-134a refrigerators.

Another possible source of electrostatic sparks is the high-speed flashing flow of refrigerant coming out of a small orifice, such as a leak hole or severed capillary tube.

This can happen in the event of a leak after the capillary tube and before the evaporator as described in UL standard 250. Electrostatic discharges in capillary tubes have been reported in scientific literature (e.g. Schultz, 1985; Yana Motta el at., 2002). Static sparks have of energies up to 30 mJ and are sufficient to ignite hydrocarbon refrigerants.

3. <u>Defrost Heater</u>

The defrost heater can fail in two ways: it can generate an electrical spark at exposed terminals or connections or it can short causing a region of temperature exceeding the safe sheath operating temperature. Normal operating cycles have the defrost heater activating for a period of about 10 minutes, three times a day (or 2% of time) normally distributed. We would expect the electrical connections or rubber boot to fail on the order of 1 ppm (one refrigerator per million per year). We expect metal sheath heaters will be utilized for mass production in the US (as opposed to some fragile quartz designs). The vibrations and handling of metal sheath heaters will likely contribute to such heaters exceeding the safe operating temperature at approximately 10 ppm. (Note: this does not generate an operational fault for R-134a refrigerators and is not detected today because the heater will still defrost the evaporator coil, albeit at elevated temperatures.)

4. <u>Defrost Heater – Coupled Leak Scenario</u>

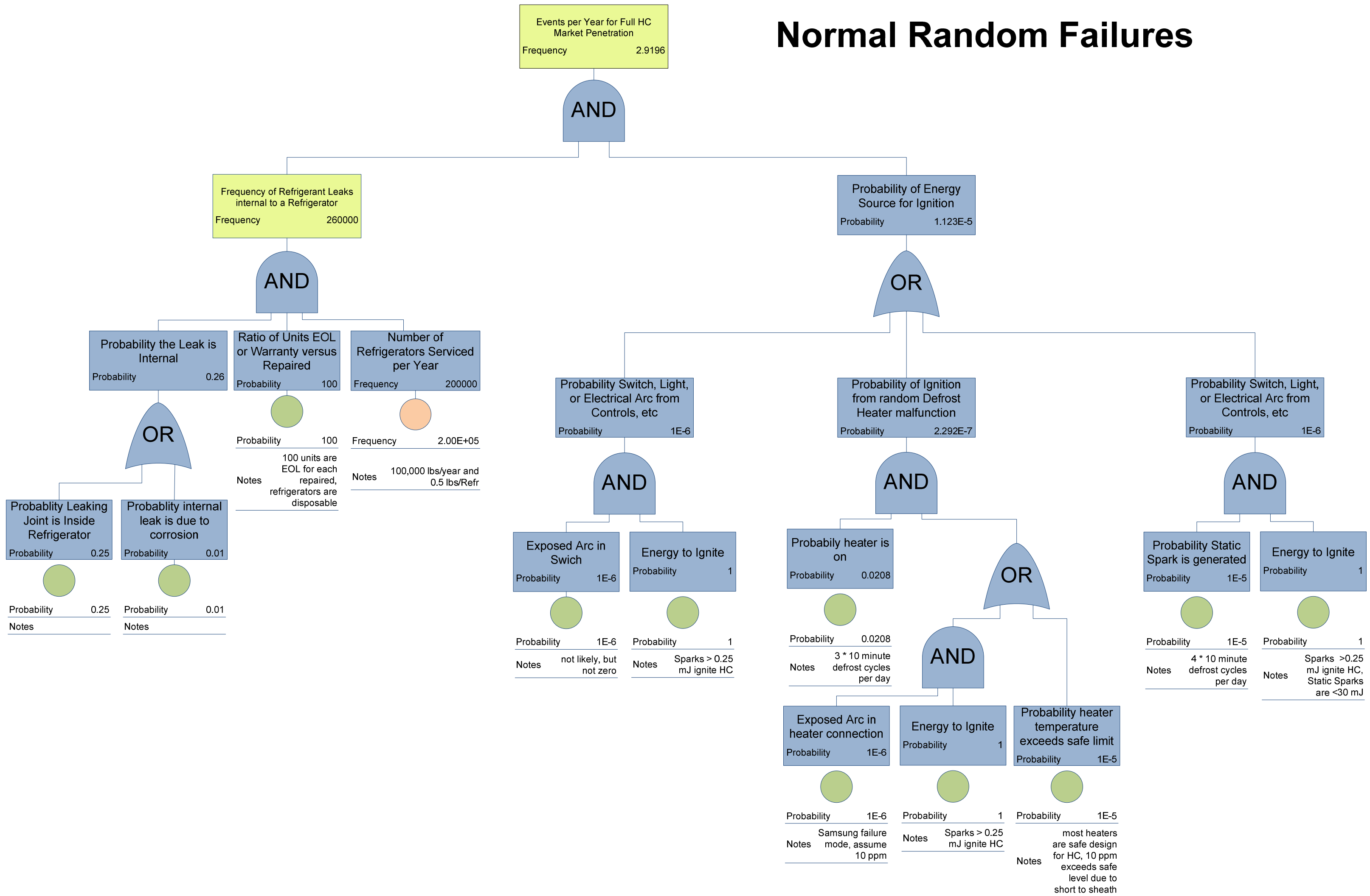
The defrost heater can generate an electrical spark at exposed terminals or connections and cause a refrigerant leak. While we have concerned ourselves with random, independent events for all other failure scenarios, the defrost heater presents a coupled failure mechanism because <u>an electrical short to the evaporator coil can be both the cause of a refrigerant leak and the ignition event</u>. Conservatively, we put this failure at the same level of normal defrost heater failure, 1 ppm. Even with the 100 times EOL/repair ratio for all other failure modes, this failure mode becomes the dominate failure mode for flammable refrigerants and the extent of damage becomes dependent on the energy release and flame stability of the gas. Hydrocarbons fail in dramatic fashion in this mode because they have very high flame speeds (high flame stability) and high deflagration indexes (energy release).

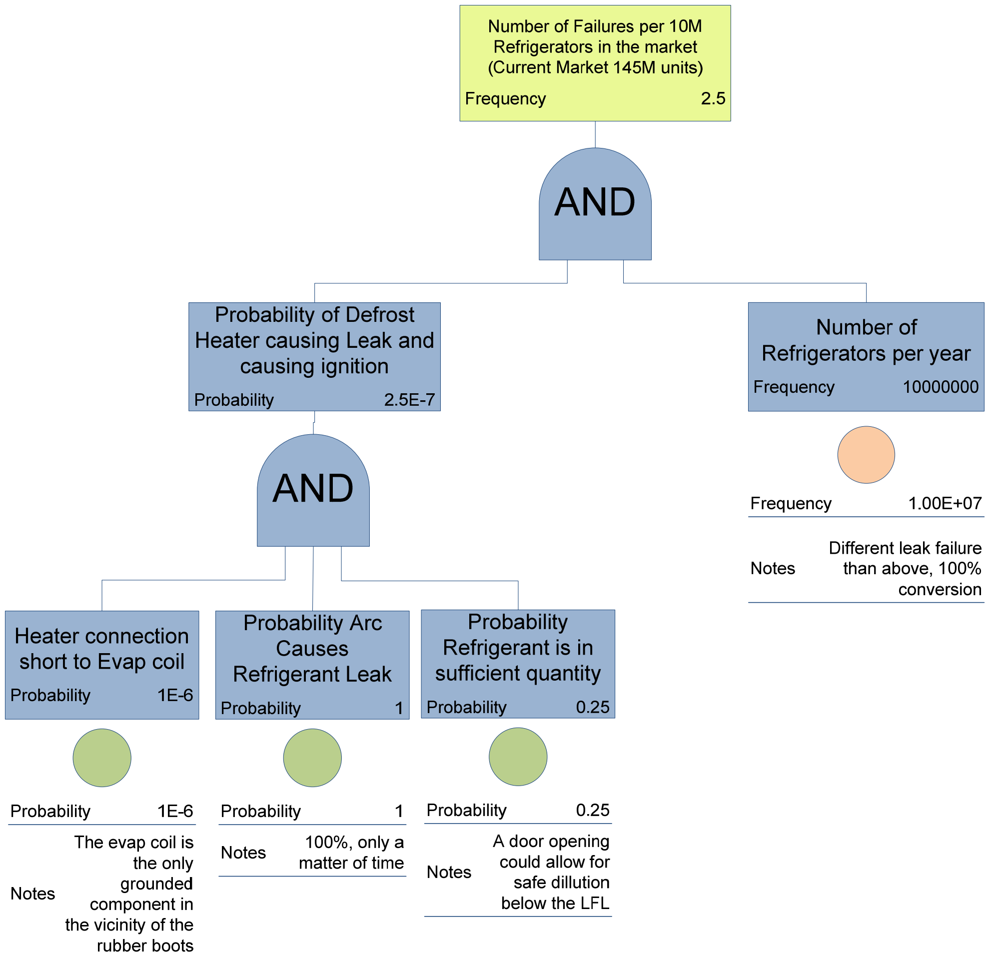
C. Honeywell encourages the EPA to conduct additional risk analysis review prior to approving HCs for safe use in U.S. refrigerators

We feel that EPA's AD Little risk assessment potentially under-estimates the ignition-related failures in residential refrigerators for internal leak events. We put forth our risk assessment for analysis and conclude that if hydrocarbons are allowed to reach full market penetration over the course of the next 10 years, there could be three ignition-related events per year due to normal practice. We also find additional cause for concern that there will be ignitions due to electrical arcs from the defrost heater that cause a leak in the evaporator. This scenario would generate both flammable concentrations and sufficient energy to ignite the material and will occur at a cumulative rate of 5.5 events per year at maturity unless special precautions are incorporated. Our fault tree analysis is shown below.

	Event Frequency	**Notes:**
Mature Market Penetration (electrical, static, heater temp)	3 events/year	10 years to reach maturity
Defrost Heater Coupled Leak	2.5 events/year	random from market launch

Normal Random Failures




Number of Failures per 10M Refrigerators in the market (Current Market 145M units)
Frequency 2.5
AND
Probability of Defrost Heater causing Leak and causing ignition
Probability 2.5E-7
Number of Refrigerators per year
Frequency 10000000
Frequency 1.00E+07
Notes Different leak failure than above, 100% conversion
AND
Heater connection short to Evap coil
Probability 1E-6
Probability Arc Causes Refrigerant Leak
Probability 1
Probability Refrigerant is in sufficient quantity
Probability 0.25
Probability 1E-6
Notes The evap coil is the only grounded component in the vicinity of the rubber boots
Probability 1
Notes 100%, only a matter of time
Probability 0.25
Notes A door opening could allow for safe dillution below the LFL

III. Honeywell's Leak Concentration Measurements and Field Test Show the Risk of Flammability When Using HCs In Refrigerators.

A. Use of Isobutane (R-600a) in Refrigerators

1. <u>Refrigerant Concentrations (internal and external leaks)</u>

i. External leaks

Risk assessment documents available on the EPA SNAP docket suggest that external leaks of refrigerant distribute homogeneously in the ambient (kitchen). The highest risk scenarios available in the EPA SNAP docket assume distribution in the lower part of the room (0.4 m high). However, previous risk assessment documents do not take into account the installation/geometry of a typical U.S. kitchen. Refrigerators are often enclosed between cabinets and near external ignition sources such as electrical plugs, ranges, ovens and others. Furthermore, a leak inside the compressor/condenser enclosure will likely produce high refrigerant concentrations because of its typically small volume (0.048 m^3 for the 25 cu ft refrigerator tested).

Honeywell measured isobutane concentrations using a mockup kitchen that closely resembles a typical US Kitchen. We used a bottom-freezer refrigerator located inside a control ambient chamber (see Figure 1). We followed the leak procedure according to the UL standard 250 for a high-side pressure unit resulting in:

- 57g of isobutane charge, in a 900 ml cylinder, maintained at 70ºC using a constant temperature bath;
- A cylinder connected to the leak point by a capillary tube (3m length x 0.7mm diameter); and
- A leak point which simulated a "ruptured" liquid line located before the expansion device.

Eight calibrated Henze-Hauck concentration sensors (± 0.1 vol%) were used to measure real-time concentrations of isobutane. All sensors were located near potential ignition sources (see Figures 1 and 2).

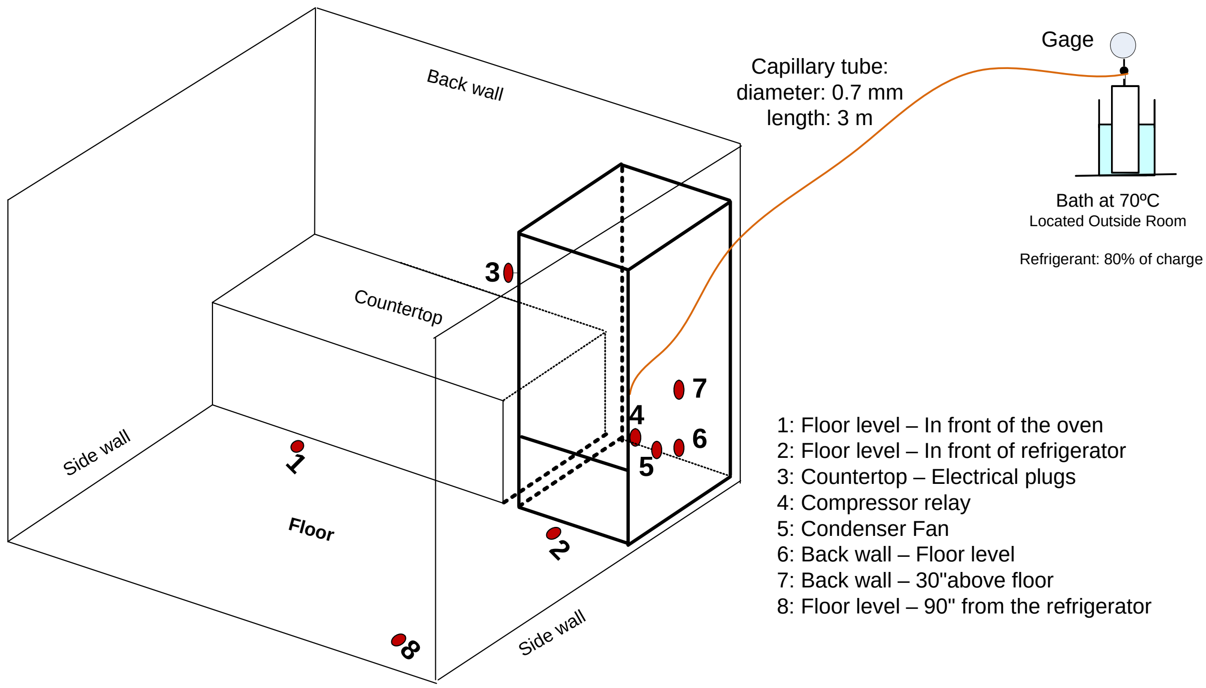


Figure 1. Mockup Kitchen

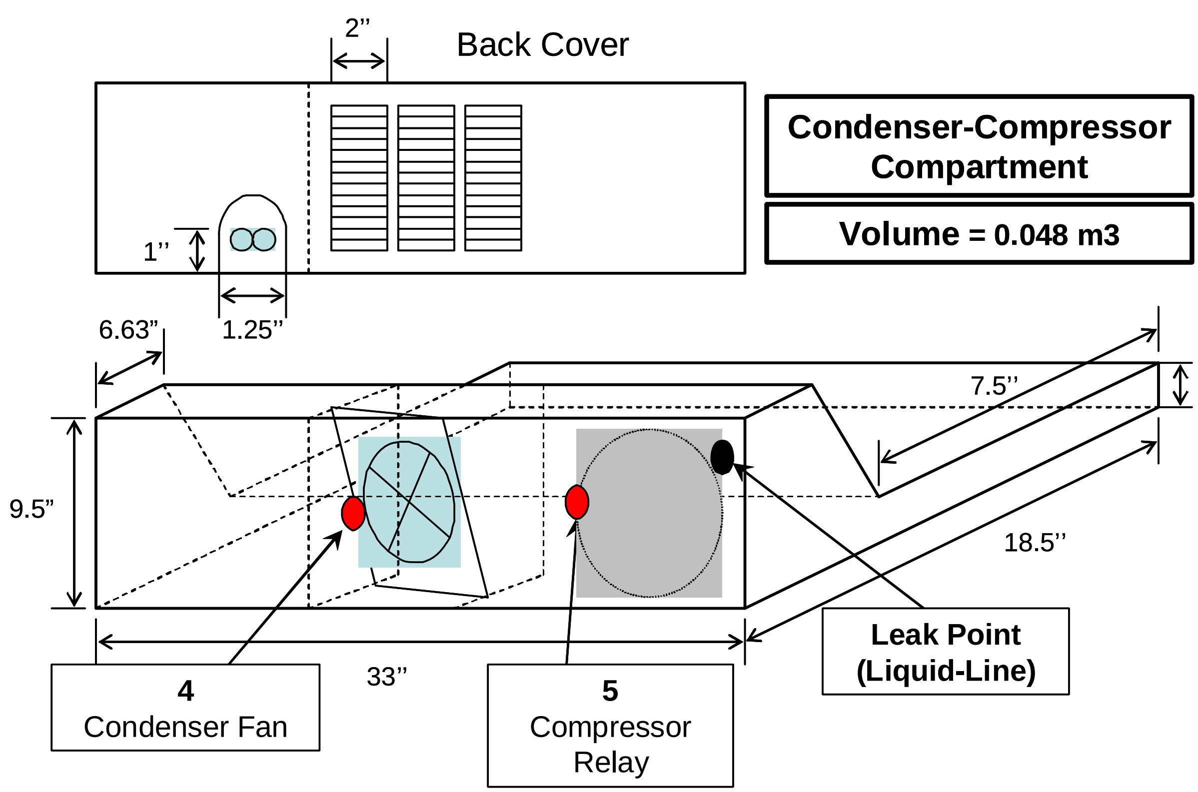


Figure 2. Back view of the condenser-compressor compartment

The results of the measurements, presented in Figure 3, show local concentrations in the flammable range for extended periods of time. Five locations show concentrations above the LFL:

- Sensor 1 (floor near the range) reaches a maximum level of 1.9% and stays above the LFL for approximately 0.6 minutes.
- Sensor 2 (floor in front of refrigerator) reaches a maximum level of 3.92% and stays above the LFL for approximately 6 minutes.
- Sensor 4 (compressor relay) reaches a maximum level of 4.28% and stays above the LFL for approximately 5 minutes.
- Sensor 6 (back wall – floor level) reaches a maximum level of 4.21% and stays above the LFL for approximately 7 minutes.
- Sensor 8 (floor 2.5 m from refrigerator) reaches a maximum level of 2% and stays above the LFL for approximately 5 minutes.

These results show that a leak can cause flammable concentrations of isobutane for periods of time longer than the assumptions put forth in the EPA cited ICF risk screens.

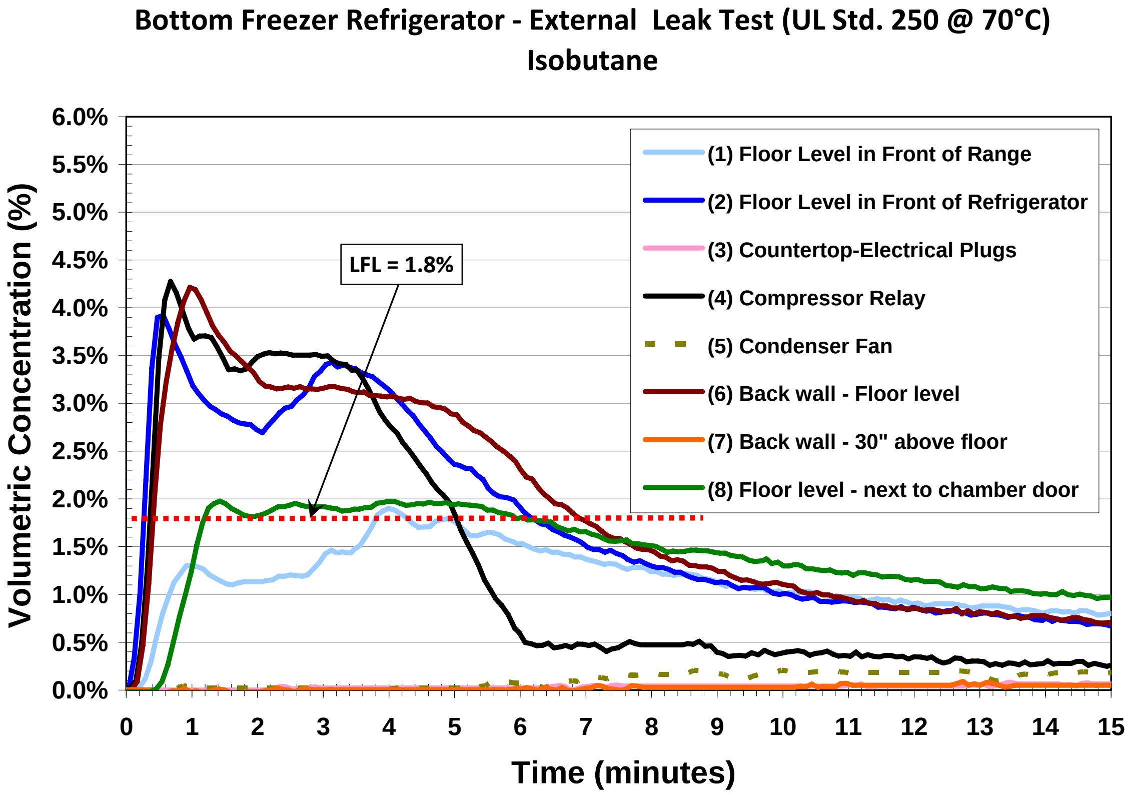


Figure 3

ii. Internal leaks

The risk assessment documents available in the EPA SNAP docket underestimate the risk of injury to human beings and structural damage to homes. In fact, a leak event as described in UL Standard 250 requires leaking 80% of the refrigerant charge, for a 25 cu ft isobutane refrigerator the leak was determined to be 57g. This amount of isobutane produces a flammable composition of 3.22%, which is far above the LFL of 1.8%.

2. <u>Test Results</u>

Honeywell performed a test to reproduce the deflagration/explosion when an internal leak is ignited, as happened in the UK case using the apparatus and procedures as shown in Figure 4 below. We tested an U.S. market refrigerator with original components, including the defrost heater, in outdoor ambient conditions (a typical spring day in Buffalo, NY). The leak apparatus was set up according to the UL Standard 250:

- small refrigerant cylinder, valves, gage and a capillary tube (3m length x 0.7mm diameter).
- Leak directed to the inlet of the evaporator.
- Refrigerant leaked a nominal charge (57g).

The sparking source simulated a faulty defrost heater connection in the freezer compartment.

We performed the leakage test as required in UL Standard 250 for low-side pressure circuit. The leak was started by opening cylinder valve. Gauge pressure was used as an indicator of the amount leaked. We then introduced a spark at the end of the leak (approx. 10 to 12 min to leak the contents into the refrigerator) and used video cameras to record the events and consequences. The cabinet integrity was inspected before and after test.

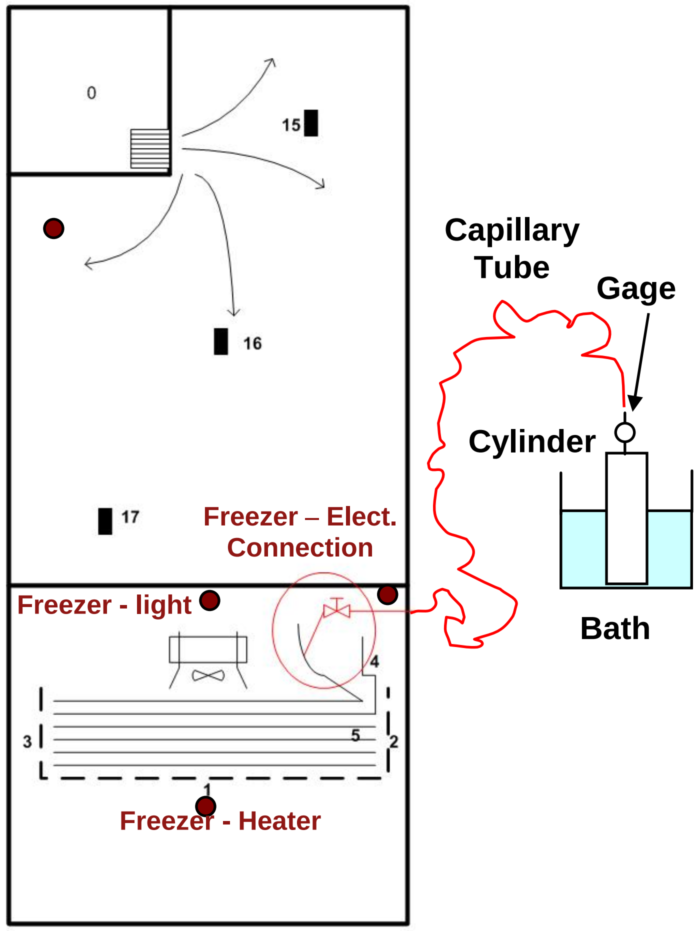


Figure 4. Internal leak and ignition test

Figure 5 below shows the result of the experiment: an extremely violent explosion which sends heavy objects like the freezer door flying up to 48 Ft. This demonstrates that 57g of isobutane produces enough energy to produce structural damage in a kitchen as shown in the UK case. Honeywell did not evaluate the risks of transporting or storing isobutane.

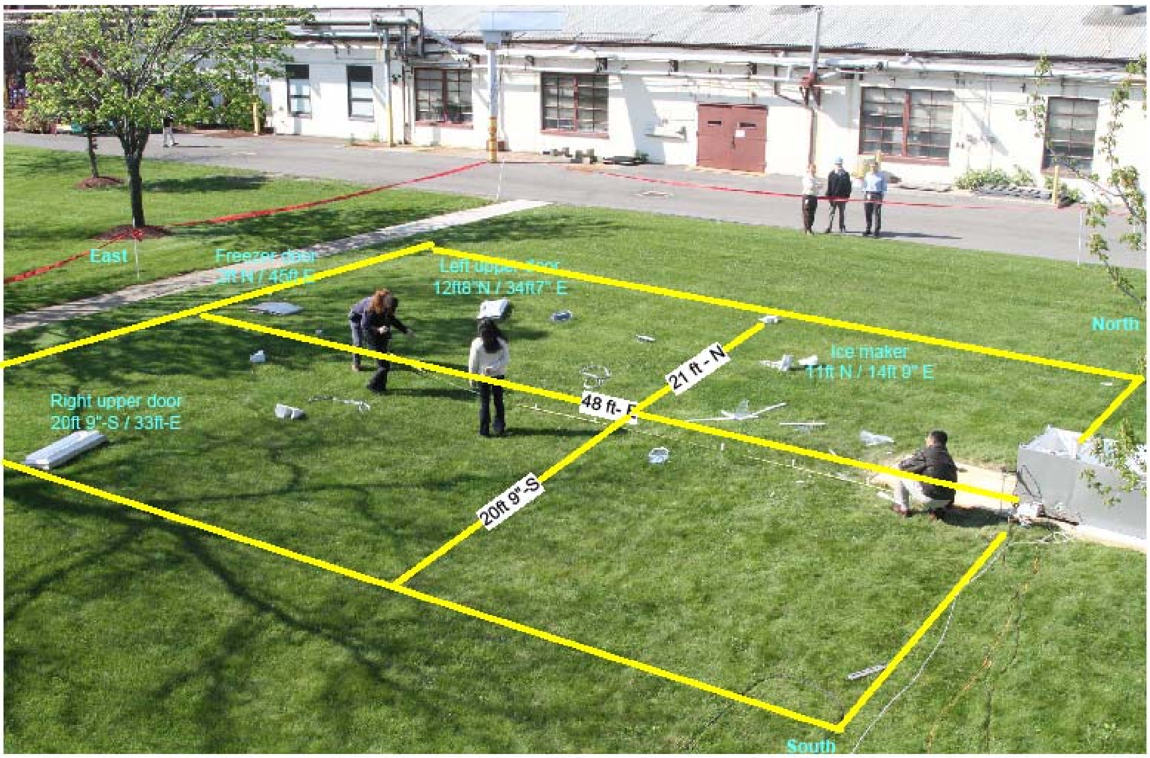


Figure 5 – Debris inspection

B. Use of Propane (R-290) in small commercial refrigeration systems

Using propane in small commercial refrigeration systems poses similar risks as using isobutane in residential refrigerators. Larger charges of HCs will result in higher risk of ignition events. These systems are also known to have much higher leakage frequencies and failure rates.

IV. Conclusion

Our measurements and test results created a cause for concern and identified additional risks not covered in the prior EPA SNAP docket submissions. The ICF Risk Screens are insufficient to address these risks because the ICF assessment: assumes that external leaks of isobutane never exceed the LFL; under-estimates the possible sources of ignition of internal isobutane leaks; and fails to address two other leak and ignition possibilities, including the scenario that occurred in the recalled refrigerators.

We recommend that EPA conduct further risk analysis that takes into account external leaks of isobutane that exceed the LFL and all internal ignition sources, including the defrost heater.

Appendix A – Refrigerator Safety Incidents in the UK

There have been several reports of accidents involving isobutane refrigerators. The latest major incident happened in the UK and originated a large recall by a manufacturer. As described in several news reports, this is a typical sequence of events:

1. The rubber seal that provides electrical insulation for the defrost heater carbonizes.
2. A partial short-circuit occurs leading to sparking.
3. Sparking corrodes the adjacent tubing causing a surface rupture and leak of isobutane.
4. Dangerous isobutane concentrations are reached at night when refrigerator doors are closed.
5. The next defrost cycle energizes the faulty electrical connection causing sparks and the consequent deflagration/explosion.