Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners

Technical Forum on Research Projects for Alternative Refrigerants in High Ambient Countries

31 October 2015

Conrad Hotel - Dubai, UAE

ORNL is managed by UT-Battelle for the US Department of Energy
Presented by

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and

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Program Objective

• Evaluate the performance of alternative lower Global Warming Potential (Low-GWP) refrigerants for mini-split air conditioning under high ambient temperatures.

• Help evaluate the viability of using alternative lower-GWP refrigerants in said markets to avoid the costly transition from HCFC to HFC and then from HFC to lower-GWP refrigerants
Panel of International Experts

Co-Chairs
Dr. Suely M. Carvalho (IPEN, Brazil) and Dr. Patrick Phelan (Department of Energy, USA)

Panel Members

- Dr. Radhey Agarwal (India)
- Dr. Karim Amrane (USA)
- Dr. Enio Bandarra (Brazil)
- Dr. J. Bhambure (India)
- Mr. Ayman El-Talouny (UNEP)
- Dr. Tingxun Li (China)
- Dr. Samuel Yana Motta (Peru)
- Mr. Maher Moussa (Kingdom of Saudi Arabia)
- Mr. Ole Nielsen (UNIDO)
- Mr. Tetsuji Okada (Japan)
- Dr. Alaa Olama (Egypt)
- Dr. Alessandro Giuliani Peru (Italy)
Panel Tasks

• Provide independent technical input for the ORNL study
• Recommend alternative refrigerants to be tested
• Review and comment on appropriate test procedures
• Assess results
• Review the interim working paper and the final report
Panel Overall Timeline

- Mid March: First Conference Call
- Mid April: Meeting in Bangkok
- Mid June: Review Interim Report
- Early July: Publish Interim Report
- Early August: Meeting in Yokohama
- Early September: Review Final Report
- Mid October: Final Report Published

Meeting of the Parties
Final Report Available

- ORNL/TM-2015/536
Evaluation Program
Why ORNL

• User facilities and flagship modeling capabilities
• Decades of experience in alternative refrigerant evaluation programs:
  – CFC phaseout strategy
  – Global Warming Impacts of Ozone-Safe Refrigerants and HVAC&R Technologies
  – Global total equivalent warming impact (TEWI) analysis of HFC refrigerants and emerging technologies
Industry Support

- **Equipment supplier: Carrier (Larry Burns)**
  - Designed for high-ambient performance up to 55°C
  - Rated capacity at ISO T1 = 5.28 kW (18 kBtu/h)
  - Rated coefficient of performance (COP): 2.78 for the R-22 baseline unit and 3.37 for the R-410A baseline unit

- **Refrigerant supplier:**
  - Honeywell (Ankit Sethi)
  - Chemours (previously Dupont) (Barbara Minor)
  - Mexichem (Sean Cunningham)
  - Arkema (Laurent Abbas)

- **AHRI (Xudong Wang)**
## R-22 Alternative Refrigerants

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Manufacturer</th>
<th>ASHRAE safety class</th>
<th>GWP&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-22</td>
<td>–</td>
<td>A1</td>
<td>1,810 1,760</td>
</tr>
<tr>
<td>N-20B&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Honeywell</td>
<td>A1</td>
<td>988 904</td>
</tr>
<tr>
<td>DR-3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Chemours</td>
<td>A2L</td>
<td>148 146</td>
</tr>
<tr>
<td>ARM-20B&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Arkema</td>
<td>A2L</td>
<td>251 251</td>
</tr>
<tr>
<td>L-20A&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Honeywell</td>
<td>A2L</td>
<td>295 295</td>
</tr>
<tr>
<td>DR-93&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Chemours</td>
<td>A1</td>
<td>1,258 1,153</td>
</tr>
<tr>
<td>R-290</td>
<td>–</td>
<td>A3</td>
<td>3 3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Sources: IPCC AR4, 2007; IPCC AR5, 2013.

<sup>b</sup> GWP values for refrigerant blends not included in IPCC reports are calculated as a weighted average using manufacturer-supplied compositions.
### R-410A Alternative Refrigerants

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Manufacturer</th>
<th>ASHRAE safety class</th>
<th>GWP(^{a})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AR4</td>
</tr>
<tr>
<td>R-410A</td>
<td>–</td>
<td>A1</td>
<td>2088</td>
</tr>
<tr>
<td>ARM-71A(^{b})</td>
<td>Arkema</td>
<td>A2L</td>
<td>460</td>
</tr>
<tr>
<td>R-32</td>
<td>Daikin</td>
<td>A2L</td>
<td>675</td>
</tr>
<tr>
<td>DR-55(^{b})</td>
<td>Chemours</td>
<td>A2L</td>
<td>698</td>
</tr>
<tr>
<td>L-41(^{b})</td>
<td>Honeywell</td>
<td>A2L</td>
<td>583</td>
</tr>
<tr>
<td>HPR-2A(^{b})</td>
<td>Mexichem</td>
<td>A2L</td>
<td>600</td>
</tr>
</tbody>
</table>

\(^{a}\) Sources: IPCC AR4, 2007; IPCC AR5, 2013.

\(^{b}\) GWP values for refrigerant blends not included in IPCC reports are calculated as a weighted average using manufacturer-supplied compositions.
**Test Conditions**

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Outdoor</th>
<th></th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry-bulb temp.</td>
<td>Dry-bulb temp.</td>
<td>Wet-bulb temp.</td>
</tr>
<tr>
<td>AHRI B</td>
<td>°C (°F)</td>
<td>°C (°F)</td>
<td>°C (°F)</td>
</tr>
<tr>
<td>AHRI A</td>
<td>27.8 (82.0)</td>
<td>26.7 (80.0)</td>
<td>19.4 (67.0)</td>
</tr>
<tr>
<td>T3*</td>
<td>35.0 (95.0)</td>
<td>26.7 (80.0)</td>
<td>19.4 (67.0)</td>
</tr>
<tr>
<td>T3</td>
<td>46 (114.8)</td>
<td>26.7 (80.0)</td>
<td>19 (66.2)</td>
</tr>
<tr>
<td>Hot</td>
<td>46 (114.8)</td>
<td>29 (84.2)</td>
<td>19 (66.2)</td>
</tr>
<tr>
<td>Extreme</td>
<td>52 (125.6)</td>
<td>29 (84.2)</td>
<td>19 (66.2)</td>
</tr>
</tbody>
</table>
Facilities

- Multi-Zone Environmental Chambers: “Outdoor” chamber is 6.1×4.6 m; the 8.5 m square “indoor” chamber can be divided into up to four spaces controlled at different conditions to represent separate zones. Dry-bulb temperature is controlled at −23 to 55°C (−10 to 131°F) and relative humidity at 30 to 90%.
**Instrumentation: R-22 system**

- Custom-built air enthalpy tunnel complying with AHRI Standard 210/240 and ANSI/ASHRAE Standard 37: air flow measurement uncertainty ±0.4%
- Coriolis mass flow meter: CMF25 with ±0.5% error
- Pressure sensors: ±0.08% BSL
- T-type thermocouples: ±0.28°C (0.5°F)
- Dew point sensors: ±0.2°C (0.36°F)
- Barometric pressure sensors: ±0.6 hPa/mb
- Power meters: ±0.2% reading

*All instrumentation was calibrated either by ORNL metrology or by a third-party calibration laboratory before the experimental campaign began.*
R-22 Experiment Setup
R-22 Experiment Setup

- Capillary Tube Header
- Pressure Sensor
- Instream TC
- Coriolis Mass Flow Meter
R-22 Experiment Uncertainty

• Air-side uncertainty:
  – Capacity = ±2.3%
  – COP = ±2.4%

• Refrigerant-side uncertainty:
  – Capacity = ±0.7%
  – COP = <±0.8%

• Energy balance between air-side and refrigerant-side measurements:
  – AHRI A: −2.3% to 2.89%
  – AHRI B: −1.99% to 2.37%
Instrumentation: R-410A system

- Code tester complying with AHRI Standard 210/240 and ANSI/ASHRAE Standard 37
- Coriolis mass flow meter: CMF25 with ±0.5% error
- Pressure sensors: ±0.08% BSL
- RTD: ±0.15°C (0.27°F) @ 0°C
- Wet-bulb sensors: ±0.15°C (0.27°F) @ 0°C
- Barometric pressure sensors: ±0.6 hPa/mb
- Power meters: ±0.2% reading

*All instrumentation was calibrated either by ORNL metrology or by a third-party calibration laboratory before the experimental campaign began.*
R-410A Experimental Setup
R-410A Experimental Setup
R-410A Experiment Uncertainty

• **Air-side uncertainty:**
  – Capacity: ±1.6%
  – COP: ±1.5%

• **Refrigerant-side uncertainty:**
  – Capacity: ±0.65%
  – COP: ±0.81%

• **Energy balance between air-side and refrigerant-side measurements:**
  – AHRI A: −3.6% to 0.05%
  – AHRI B: −3.97% to 0.05%
Optimization of Alternative Refrigerants

• **Optimization sequence:**
  – Optimize charge
  – Find best capillary tube
  – Increase/decrease charge
  – Find best capillary tube

• **Check performance at T3 to ensure superheat and subcooling to maintain capacity at extreme conditions**
R-22 Unit Results

Baseline: R-22 with mineral oil
## R-22 Unit

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Manufacturer</th>
<th>ASHRAE safety class</th>
<th>Charge mass kg (oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-22 (baseline)</td>
<td>–</td>
<td>A1</td>
<td>1.417 (50)</td>
</tr>
<tr>
<td>N-20B</td>
<td>Honeywell</td>
<td>A1</td>
<td>2.087 (73.6)</td>
</tr>
<tr>
<td>DR-3</td>
<td>Chemours</td>
<td>A2L</td>
<td>2.007 (70.8)</td>
</tr>
<tr>
<td>ARM-20B</td>
<td>Arkema</td>
<td>A2L</td>
<td>1.588 (56)</td>
</tr>
<tr>
<td>L-20A (R-444B)</td>
<td>Honeywell</td>
<td>A2L</td>
<td>1.568 (55.3)</td>
</tr>
<tr>
<td>DR-93</td>
<td>Chemours</td>
<td>A1</td>
<td>1.828 (64.5)</td>
</tr>
<tr>
<td>R-290</td>
<td>–</td>
<td>A3</td>
<td>0.731 (25.8)</td>
</tr>
</tbody>
</table>
Impact on COP

![Bar chart showing the impact of different refrigerants on COP in various temperature conditions.]
Impact on Capacity

![Graph showing impact on capacity for different refrigerants in various temperature conditions.](image-url)
Overall Evaporator Temperature Glide

![Graph showing temperature glide at the evaporator for different refrigerants and conditions.]

- R-22/mineral oil
- L-20A (R-444B)
- DR-3
- N-20B
- ARM-20B
- R-290/POE
- DR-93

Temperature Glide at the Evaporator, °C

Overall Evaporator Temperature Glide
Impact on Compressor Discharge Temperature ($T_{\text{comp}}$)
Alternative Refrigerant Evaluation for High Ambient Temperature Environments

Performance Relative to Baseline at AHRI A Conditions 35°C (95°F) Outdoor and 27°C (80°F) Indoor

- L-20A (R-444B)
- DR-3
- N-20B
- ARM-20B
- R-290/POE

COP

Cooling Capacity
Performance Relative to Baseline at ISO T3 Conditions 46°C (114.8°F) Outdoor and 29°C (84.2°F) Indoor

COP

80% 85% 90% 95% 100% 105%

Cooling Capacity

80% 85% 90% 95% 100% 105%

R-290/POE
L-20A (R-444B)
N-20B
DR-93
DR-3
ARM-20B
Performance Relative to Baseline at Hot Conditions 52°C (125.6°F) Outdoor and 29°C (84.2°F) Indoor

COP

- R-290/POE
- L-20A (R-444B)
- N-20B
- DR-3
- DR-93
- ARM-20B

Cooling Capacity

- 80%
- 85%
- 90%
- 95%
- 100%
- 105%
Performance Relative to Baseline at Extreme Conditions 55°C (131°F) Outdoor and 29°C (84.2°F) Indoor
Performance of R-444B at Different Test Conditions

COP

80% 85% 90% 95% 100% 105%

Cooling Capacity

B A T3* T3 Extreme Hot
Performance of ARM-20A at Different Test Conditions

COP

80% 85% 90% 95% 100% 105% 110%

Cooling Capacity

80% 85% 90% 95% 100% 105%

- B
- A
- T3*
- T3
- Hot
- Extreme
Performance of R-290/POE at Different Test Conditions

<table>
<thead>
<tr>
<th>COP</th>
<th>80%</th>
<th>85%</th>
<th>90%</th>
<th>95%</th>
<th>100%</th>
<th>105%</th>
<th>110%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- B
- A
- T3*
- T3
- Hot
- Extreme
## R-410A Unit

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Manufacturer</th>
<th>ASHRAE safety class</th>
<th>Charge mass kg (oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-410A (baseline)</td>
<td>–</td>
<td>A1</td>
<td>0.936 (33)</td>
</tr>
<tr>
<td>ARM-71A</td>
<td>Arkema</td>
<td>A2L</td>
<td>0.765 (27)</td>
</tr>
<tr>
<td>R-32</td>
<td>Daikin</td>
<td>A2L</td>
<td>0.709 (25)</td>
</tr>
<tr>
<td>DR-55</td>
<td>Chemours</td>
<td>A2L</td>
<td>0.811 (28.6)</td>
</tr>
<tr>
<td>L-41 (R-447A)</td>
<td>Honeywell</td>
<td>A2L</td>
<td>0.780 (27.5)</td>
</tr>
<tr>
<td>HPR-2A</td>
<td>Mexichem</td>
<td>A2L</td>
<td>0.808 (28.5)</td>
</tr>
</tbody>
</table>
Impact on COP

![COP Graph]

- **R-410A**
- **R-32**
- **DR-55**
- **L-41 (R-447A)**
- **ARM-71a**
- **HPR-2A**
Impact on Capacity

![Bar chart showing the impact on capacity of different refrigerants in various ambient temperature environments.](chart.png)

- **Cooling Capacity, kW**
- **B, A, T3*, T3, Hot, Extreme**
- **Refrigerants**:
  - R-410A
  - R-32
  - L-41 (R-447A)
  - DR-55
  - ARM-71a
  - HPR-2A
Impact on Compressor Discharge Temperature

![Graph showing the impact of different refrigerants on compressor discharge temperature.](image-url)
Performance Relative to Baseline at AHRI A Conditions 35°C (95°F) Outdoor and 27°C (80°F) Indoor

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>COP</th>
<th>Cooling Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-32</td>
<td>105%</td>
<td>DR-55</td>
</tr>
<tr>
<td>L-41 (R-447A)</td>
<td>90%</td>
<td>ARM-71a</td>
</tr>
<tr>
<td>HPR-2A</td>
<td>90%</td>
<td></td>
</tr>
</tbody>
</table>

Alternative Refrigerant Evaluation for High Ambient Temperature Environments
Performance Relative to Baseline at ISO T3 Conditions 46°C (114.8°F) Outdoor and 29°C (84.2°F) Indoor
Performance Relative to Baseline at Hot Conditions 52°C (125.6°F) Outdoor and 29°C (84.2°F) Indoor
Performance Relative to Baseline at Extreme Conditions 55°C (131°F) Outdoor and 29°C (84.2°F) Indoor

- L-41 (R-447A)
- HPR-2A
- DR-55
- R-32
- ARM-71a

COP

Cooling Capacity
Performance of R-32 at Different Test Conditions

- **COP**: COP (Coefficient of Performance) is plotted against Cooling Capacity.
- The graph shows different test conditions with labels for A, B, T3, T3*, and Hot Extreme.
- The performance of R-32 is evaluated at various cooling capacities.
Performance of DR-55 at Different Test Conditions

COP

80% 90% 100% 110%

Cooling Capacity

90% 95% 100% 105% 110%

T3

T3*

A

B

Hot

Extreme
Performance of HPR-2A at Different Test Conditions

- Hot
- Extreme
- T3
- T3*

COP

Cooling Capacity
R-22 Conclusions

• The A1 alternative refrigerants lagged in performance.

• Some of the A2L refrigerants showed capacity within 5% and efficiency within approximately 10% of the baseline system at ambient temperature at or above 46°C, albeit with a slightly higher compressor discharge temperature.

• The A3 refrigerant (R-290) exhibited higher efficiency; however, it did not match the cooling capacity. It also resulted in lower compressor discharge temperatures.
R-410 Conclusions

• R-32 showed better capacity and efficiency, but it resulted in higher compressor discharge temperatures.

• DR-55 had consistently higher COPs and matched the capacity at higher-ambient conditions.

• HPR-2A’s performance exceeded the baseline at all ambient temperatures higher than 35°C.

• R-447A and ARM-71a had lower capacity, but R-447A had better COP at ambient temperatures higher than 46°C.
Overall Conclusions (1)

• Under all testing conditions, the performance of the units degraded as the outdoor temperature increased.

• The obtained results are for soft-optimized systems only; the efficiency and capacity of the alternative refrigerants would be expected to improve through design modifications before a new product was introduced to market.
Overall Conclusions (2)

• Viable replacements exist for both R-22 and R-410A at high ambient temperatures.
• Multiple alternatives for R-22 performed well, and most R-410A alternatives matched or exceeded the performance of R-410A. These may be considered as prime candidate lower-GWP refrigerants for high-ambient-temperature environments.
Acknowledgment

• Extraordinary team at ORNL: Dr. Som Shrestha, Mr. Randy Linkous
• Extraordinary team at Navigant Consulting: Mr. William Goetzler, Mr. Matthew Guernsey, Theo Kassuga
• ORNL BERG/BTRIC
• BTO support
• Panel of International Experts
Questions?

- Omar Abdelaziz, abdelazizoa@ornl.gov

References
