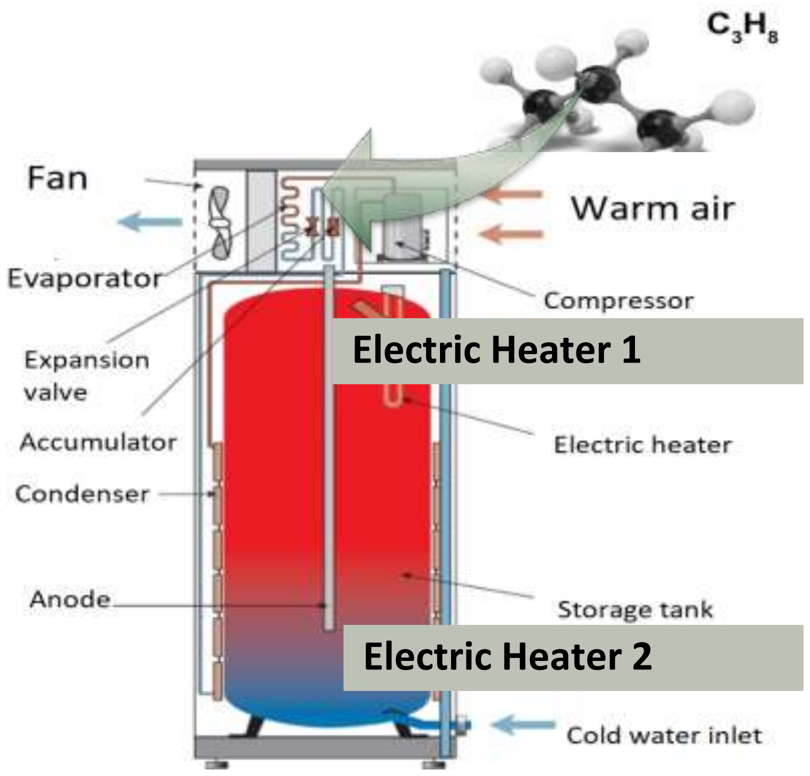
Development of Next Generation Heat Pump Water Heater Deploying Newly Emerging Refrigerants

(CRADA A.O. Smith)



Oak Ridge National Laboratory
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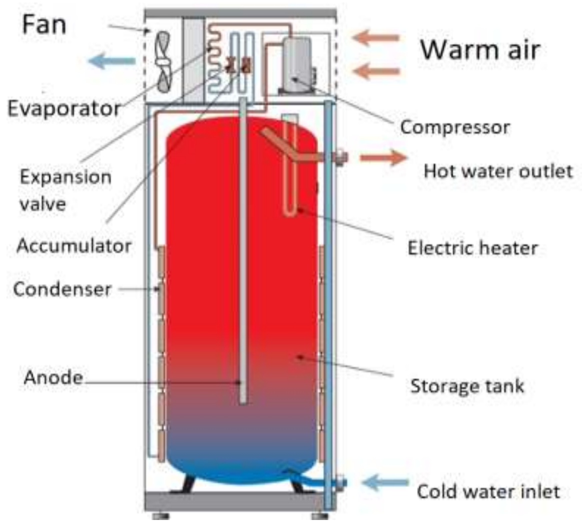
WBS # 03.02.02.41

Project Summary

Objective and outcome

- Evaluate the potential of Propane (R290) to replace R134a for a residential hybrid HPWH as a drop in replacement refrigerants.
- Evaluate various charge reduction approaches and analyze the impact of various component and system modifications on total refrigerant charge.
- Conduct field evaluation of optimized configuration.



Team and Partners

Oak Ridge National Laboratory: Kashif Nawaz, Bo Shen, Joe Rendall, Ahmed Elatar, Jian Sun

A.O. Smith: Steve Memory, Jiamin Yin, Tim Rooney

OAK RIDGE National Laboratory

AO Smith Innovation has a name.

Stats

Performance Period: March 2021 –Sept 2022

DOE budget: $80k, Cost Share: $20k

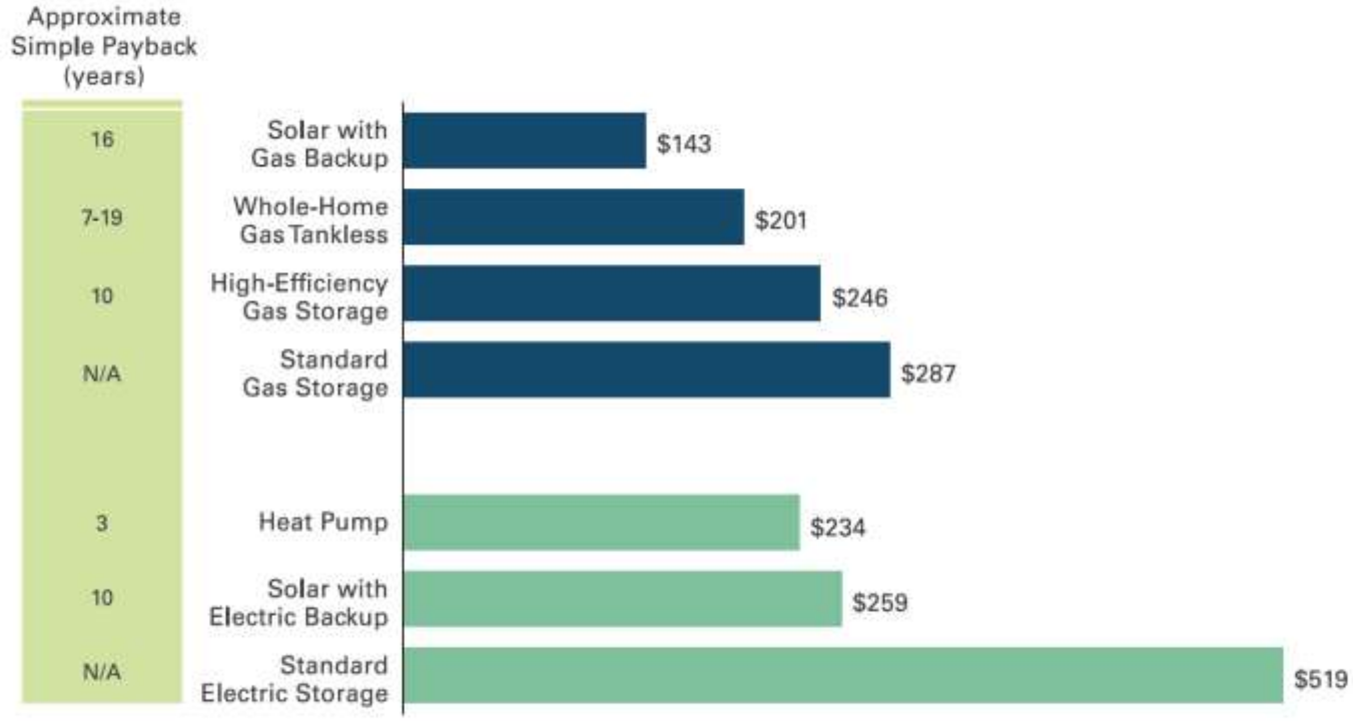
Milestone 1: Completion of thermodynamic analysis
Milestone 2: Drop-in-replacement analysis (baseline)

Milestone 3: Development of prototype for lab scale performance evaluation

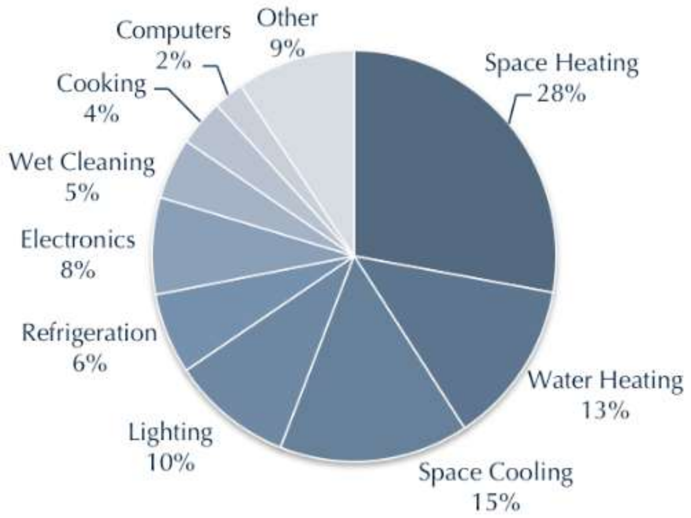
Phase I has been completed Phase II CRADA is approved

Problem

- Water heating accounts for about 10% of all residential and commercial site energy use in the United States.
- Replacement of gas-fired and electric resistive water heaters will heat pump water heaters is critical for decarbonization of buildings sector.



Annual Energy Consumption of Various Water Heating Technologies.



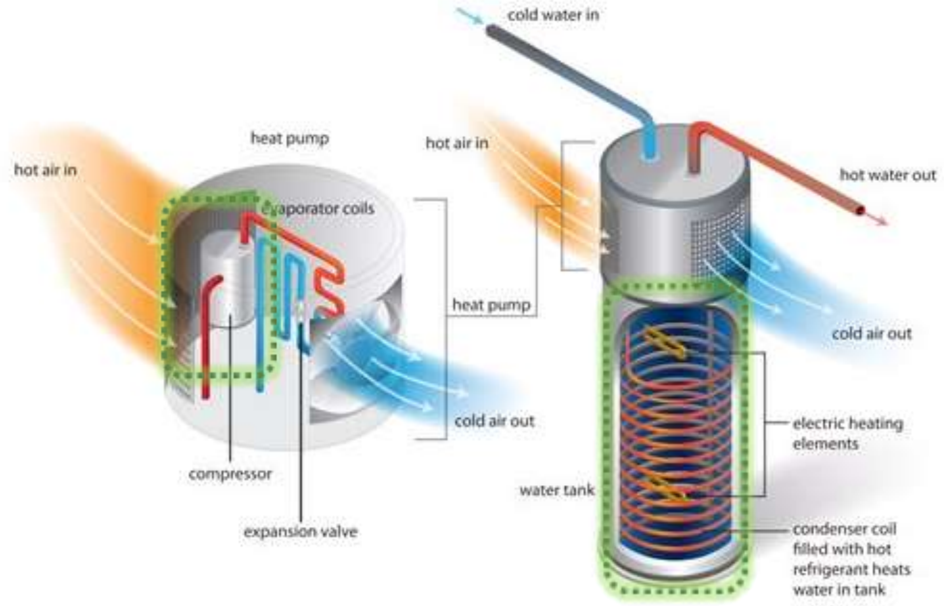
Residential end-use energy by different applications (US EIA, 2013)

Energy Star Water Heater Market Profile, D&R International, 2010

Problem

- HPWH technology has been validated and proven to be successful through lab and field experiments.
- While the technology is mature, there are obvious opportunities to further enhance the performance of the systems.

- Hybrid configuration assist to meet the demand when HP can not provide sufficient heating.
- The overall system performance depends on several factors including
  - Tank thermal stratification
  - Condenser design
  - Compressor
  - <u>**Working fluid**</u>



Operation of a HPWH

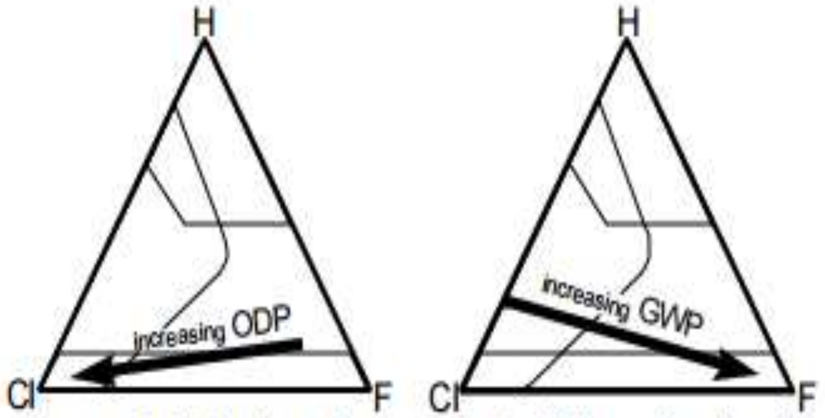
Problem

Identify appropriate substitute for R-134a as HFCs will phase out:

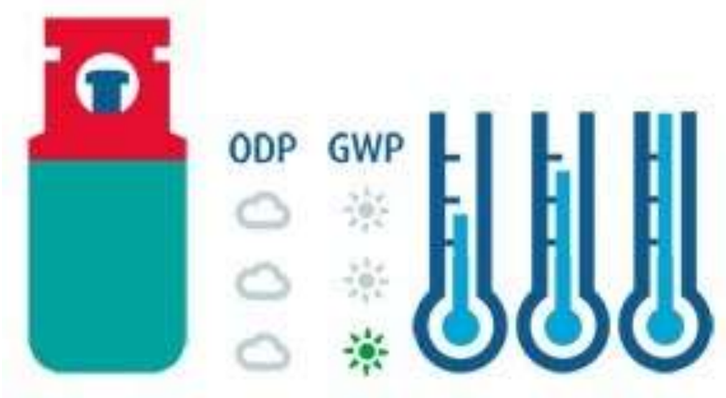
- **Evaluate the potential of Propane (R290) to replace R134a for a residential hybrid HPWH while ensuring compliance with safety standards**

  + Low GWP, no direct environmental impact
  + No major modification of existing system is desired
  + Performance FHR and UEF should be comparable
  − Refrigerants flammability poses a concern!!

Chemical compounds

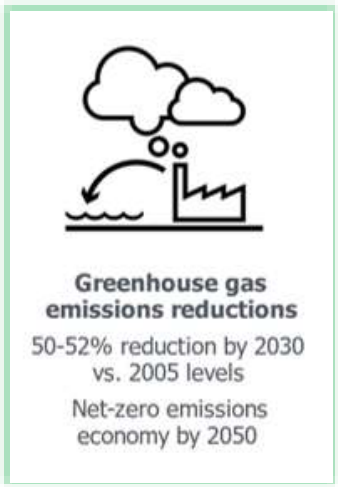


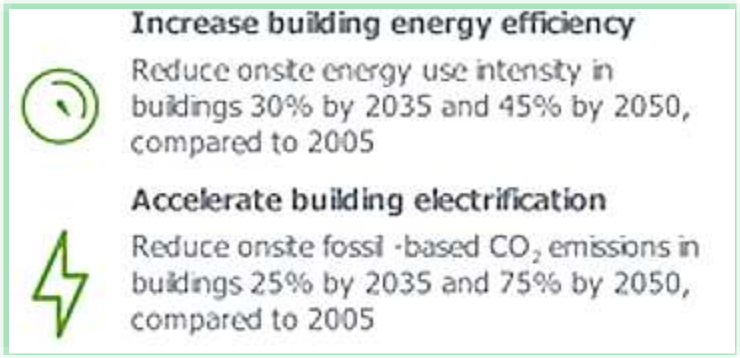
Away from Chlorine (ODP) and Fluorine (GWP) inevitably leads to flammability



Project Impact

- At least 250TBtu energy saving in water heating technology.
- More than 100Mt CO_2 emission reduction (direct and indirect)
- Enabling development for deployment of A2L and A3 refrigerants
  - Reduction in refrigerant charge
  - Reduced cost of the working fluid
  - Reduced required maintenance due to compact design
- Implications for additional processes
  - Residential air cooling/heating, refrigeration, Process water heating
- Opportunities to create more than 4000 new jobs
- Paving the path for US manufacturer to expand to international markets





Aligned with BTO goal to develop energy efficient technology to decarbonize building sector by 2050 (Net-Zero GHG Emissions)

Approach- Workplan

Phase I

- Establishment of maximum allowable charge (UL 335-2-24)
- Drop-in-replacement, charge optimization (UEF and FHR)
- Compressor replacement and performance evaluation
- Condenser design modification and performance evaluation

Phase II

- Design evaluation of evaporator (sizing, circuiting)
- Advanced condenser design-maximum thermal stratification
- Lab scale evaluation of beta prototype with modifications
- Field evaluation in three climate zones (e.g., cold climate)

Development and field demonstration of a propane-based heat pump water heater with acceptable refrigerant inventory (<150 grams) and performance (UEF>3.0).

Approach- Alternative Refrigerants

	R134a	R290
Formula	CH_2FCF_3	C_3H_8
CAS number	811-97-2	74-98-6
Molecular mass (g/mol)	102	44
Ozone depletion potential	0	0
Global warming potential, GWP_{100}	1300[a]	<3[a]
Safety classification[b]	A1	A3
Critical temperature (K)[c]	374.21	369.89
Critical pressure (MPa)[c]	4.06	4.25
Saturation pressure at 280.37 K (MPa)	0.3774	0.5879
Enthalpy of vaporization at 280.37 K (kJ/kg)	193.17	364.46
Vapor density at 280.37 K (kg/m^3)	18.66	12.75
Volumetric capacity at 280.37 K (kJ/m^3)	**3604.55**	**4646.87**
Saturation pressure at 341.48 K (MPa)	2.04	2.50

[a] IPCC 5th report, chapter 8 (Myhre et al., 2013)

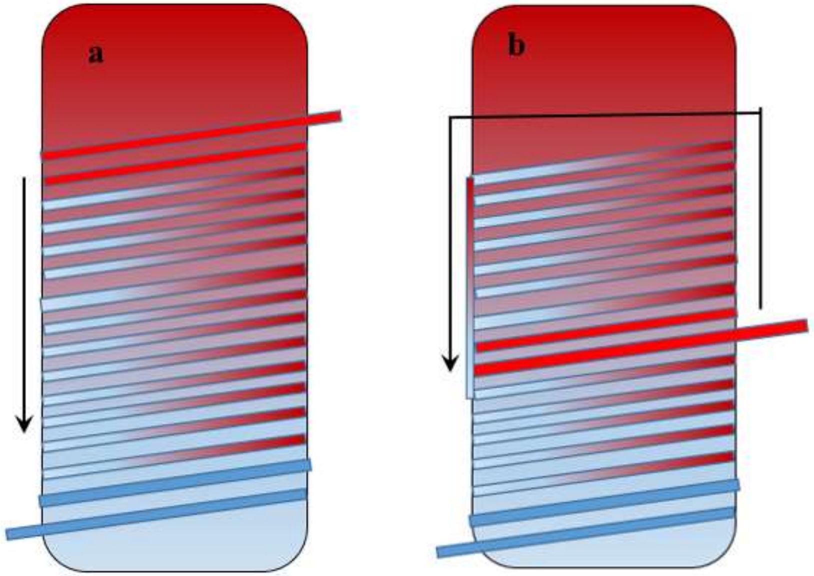
[b] ANSI/ASHRAE standard 34-2013 (A, nontoxic; 1, nonflammable; 3, flammable)

[c] REFPROP 9.1 (Lemmon et al., 2013)

Design Parameters

- Heat pump T-stat at the top: on at 115 °F, off at 125 °F.
- Electric element at the top: on at 110°F, off at 125 °F.
- Two different condenser coil wrap patterns

Case number	Wrap pattern	Tank insulation effectiveness (%)
1	Parallel-counterflow	90
2	Parallel-counterflow	95
3	Counterflow	90
4	Counterflow	95



Condenser wrap configurations: (a) counterflow, (b) parallel-counterflow

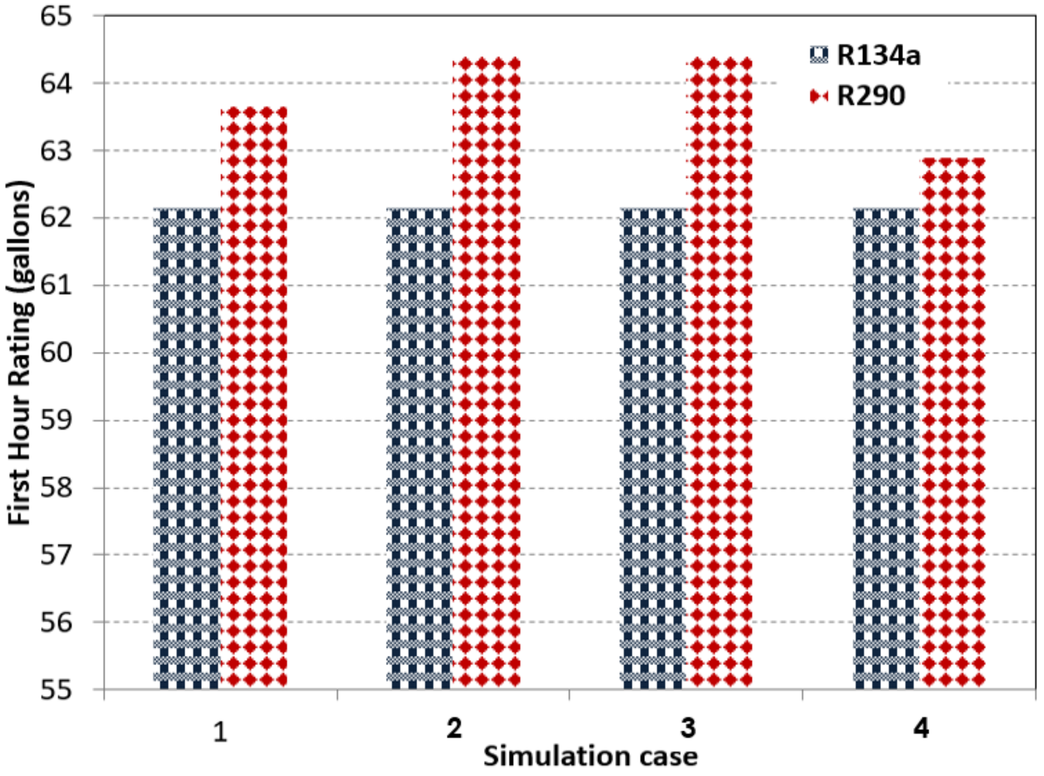
Performance Evaluation Criteria

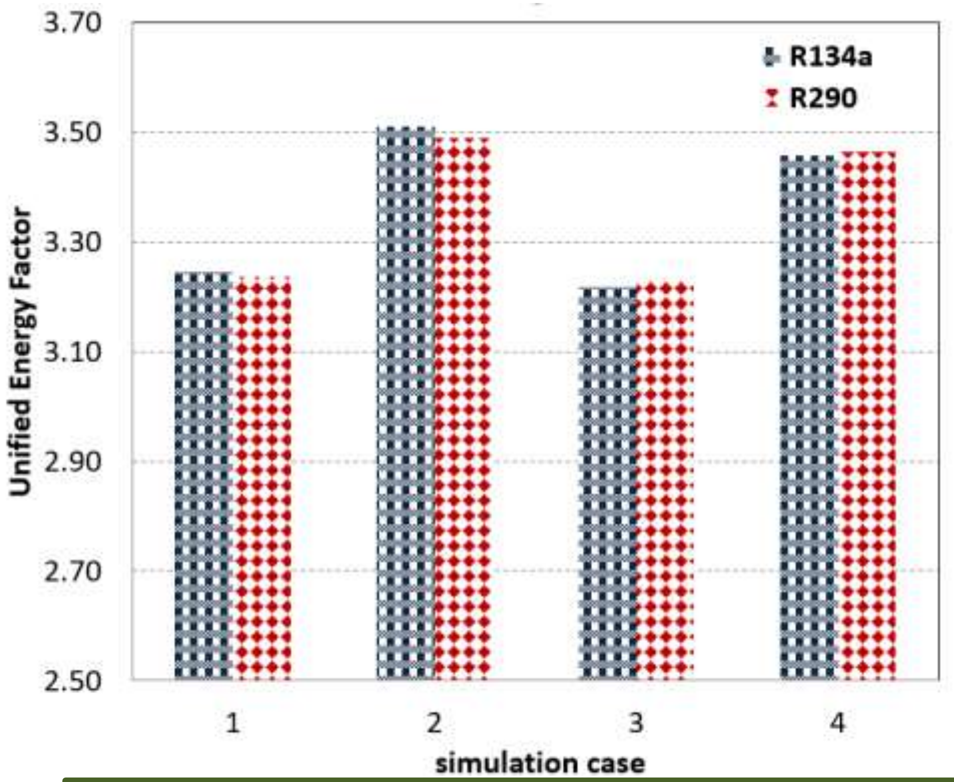
FHR greater or equal to (gals)	FHR less than (gals)	Draw pattern for 24-hr UEF
0	20	Point of use
20	55	Low usage
55	80	Medium usage
80	Max	High usage

Draw Number	Time During Test (hh:mm)	Volume (gals/L)	Flow Rate (GPM/LPM)
1	00:00	15.0 (56.8)	1.7 (6.5)
2	00:30	2.0 (7.6)	1 (3.8)
3	01:40	9.0 (34.1)	1.7 (6.5)
4	10:30	9.0 (34.1)	1.7 (6.5)
5	11:30	5.0 (18.9)	1.7 (6.5)
6	12:00	1.0 (3.8)	1 (3.8)
7	12:45	1.0 (3.8)	1 (3.8)
8	12:50	1.0 (3.8)	1 (3.8)
9	16:00	1.0 (3.8)	1 (3.8)
10	16:15	2.0 (7.6)	1 (3.8)
11	16:45	2.0 (7.6)	1.7 (6.5)
12	17:00	7.0 (26.5)	1.7 (6.5)
Total Volume Drawn Per Day: 55 gallons (208 L)			

Medium usage draw pattern

First Hour Rating (FHR) and Uniform Energy Factor (UEF)





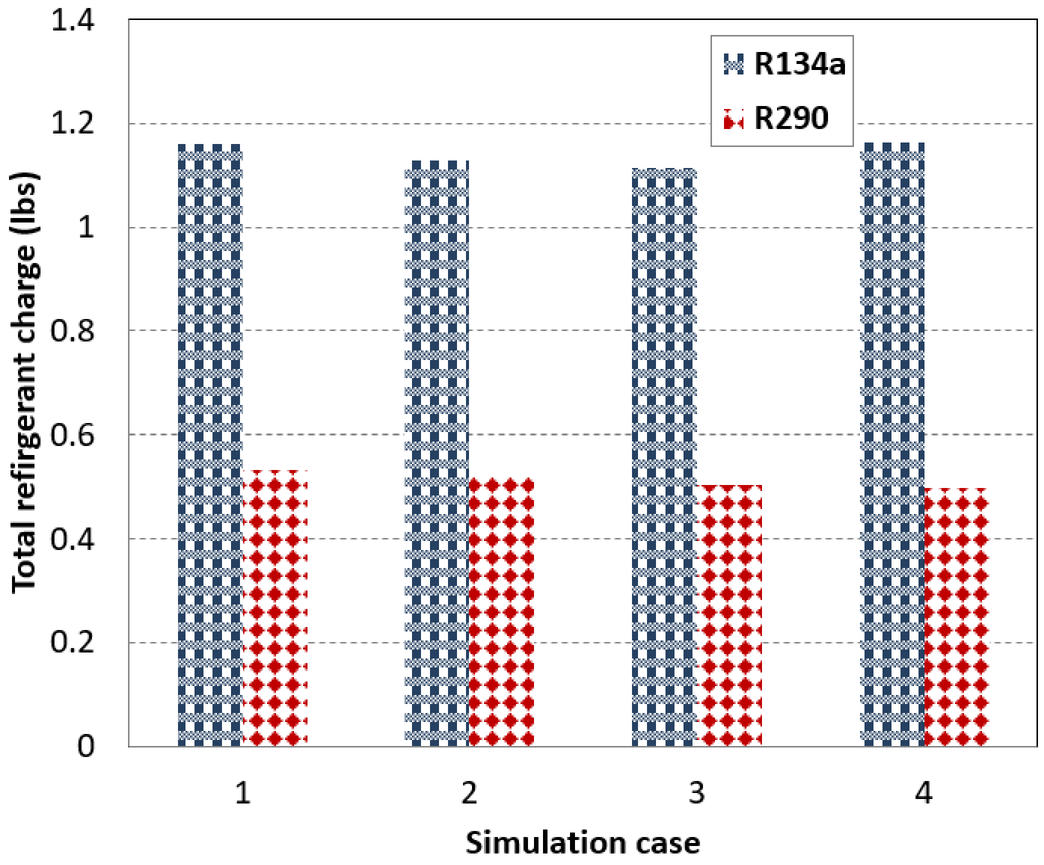
The **First Hour Rating (FHR)** is a measure of the available hot water capacity of the water heater (in gallons).

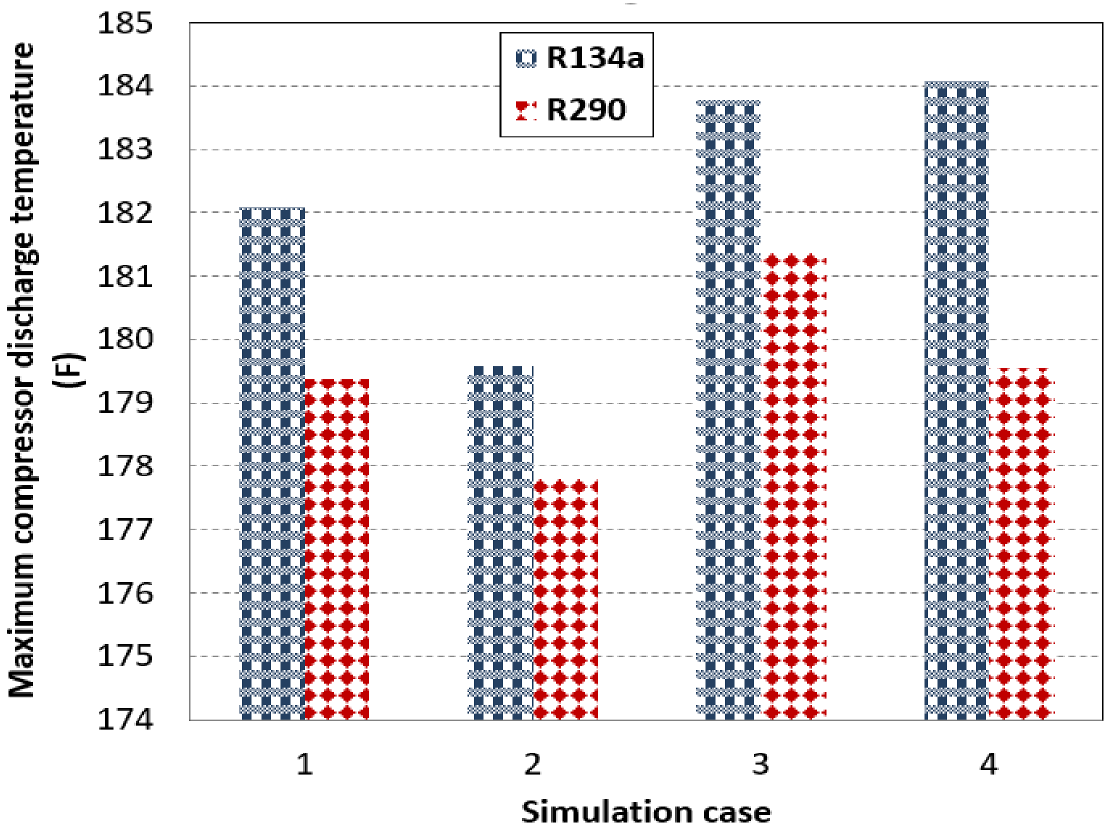
Uniform Energy Factor(UEF)

$$= \sum_{k=1}^{n} \frac{M_k c_p (T_s - T_i)}{W_i}$$

K. Nawaz, B. Shen, A. Elatar, V. Baxter, O. Abdelaziz, “R-290 and R-600a as Natural Refrigerants for Residential Heat Pump Water Heaters,” Applied Thermal Engineering, 2017, 127, 870–883

Compressor Discharge Temperature and Refrigerant Charge Inventory





Direct refrigerant replacement leads to a major charge reduction, mainly due to thermo-physical properties

Lower compressor discharge is always advantageous for direct replacement

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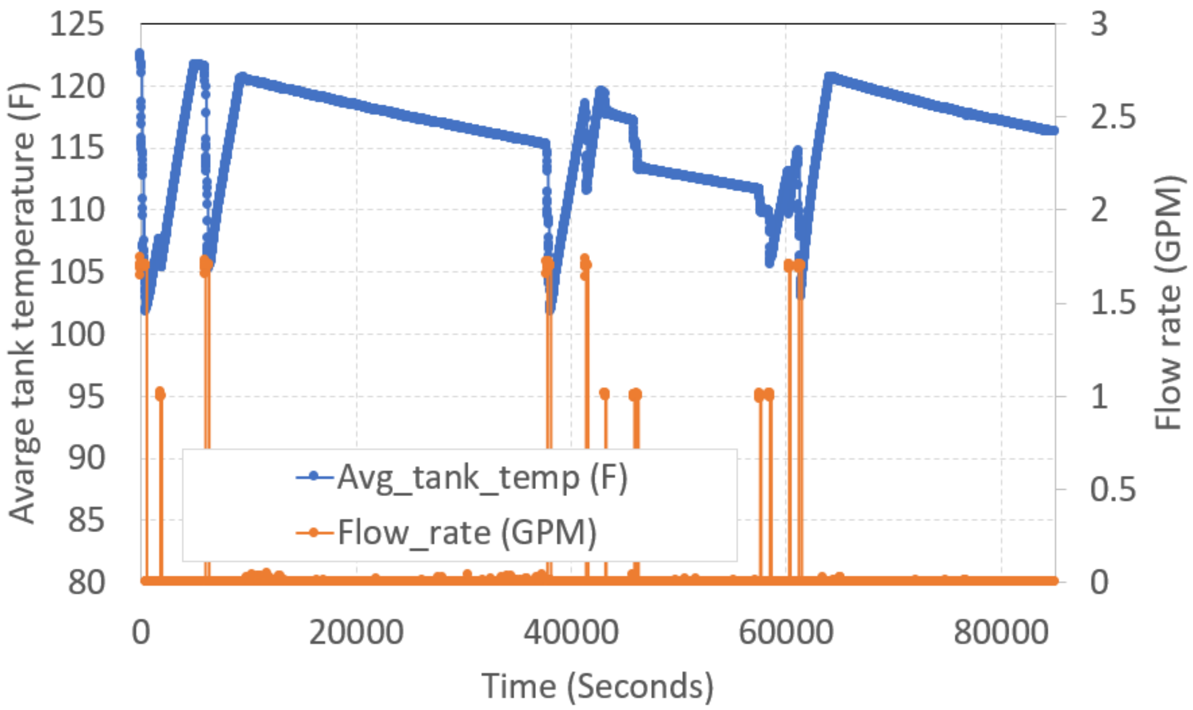
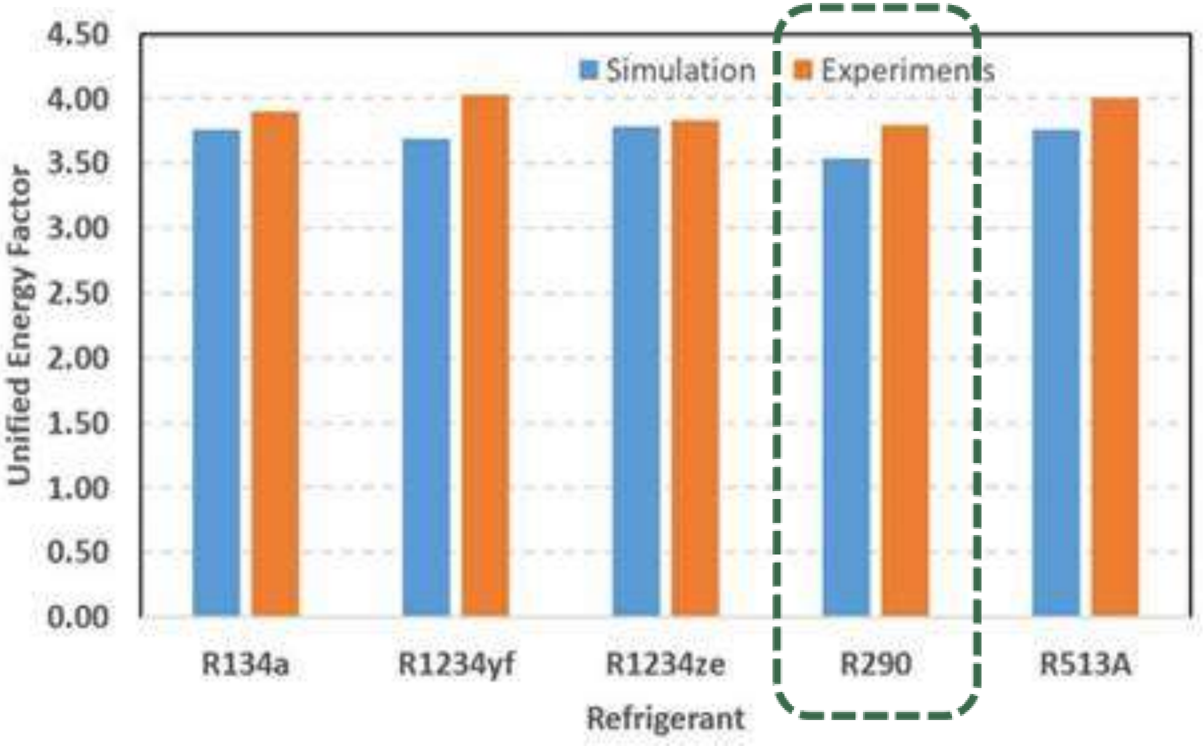
Experimental Validation



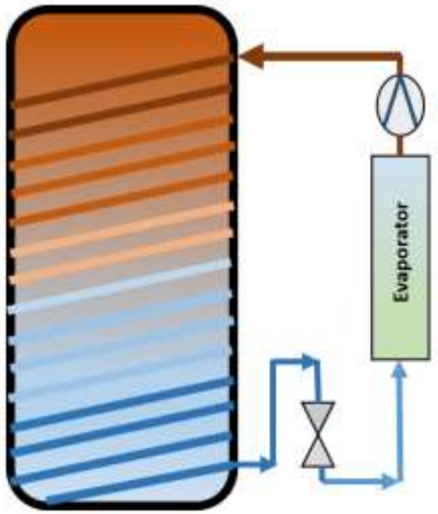


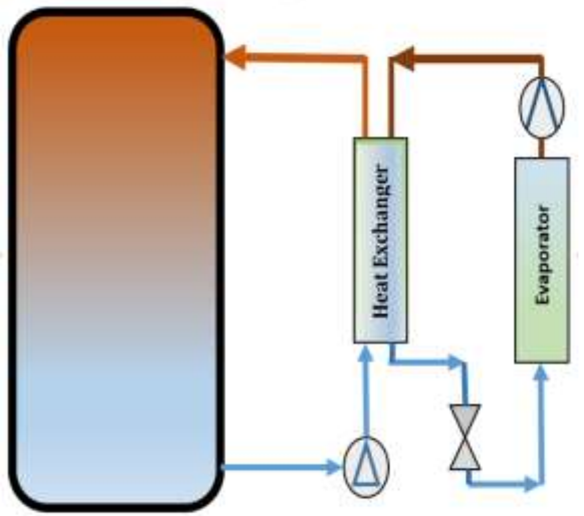
Average stored water temperature for propane is comparable to R134a.

Parameter	R134a	Propane (R290)
Optimum refrigerant charge	1.68 lbs	0.85 lbs
First Hour Rating (FHR)	66 gallons	64 gallons
Unified Energy Factor	3.44	3.60

Opportunities for Charge Reduction

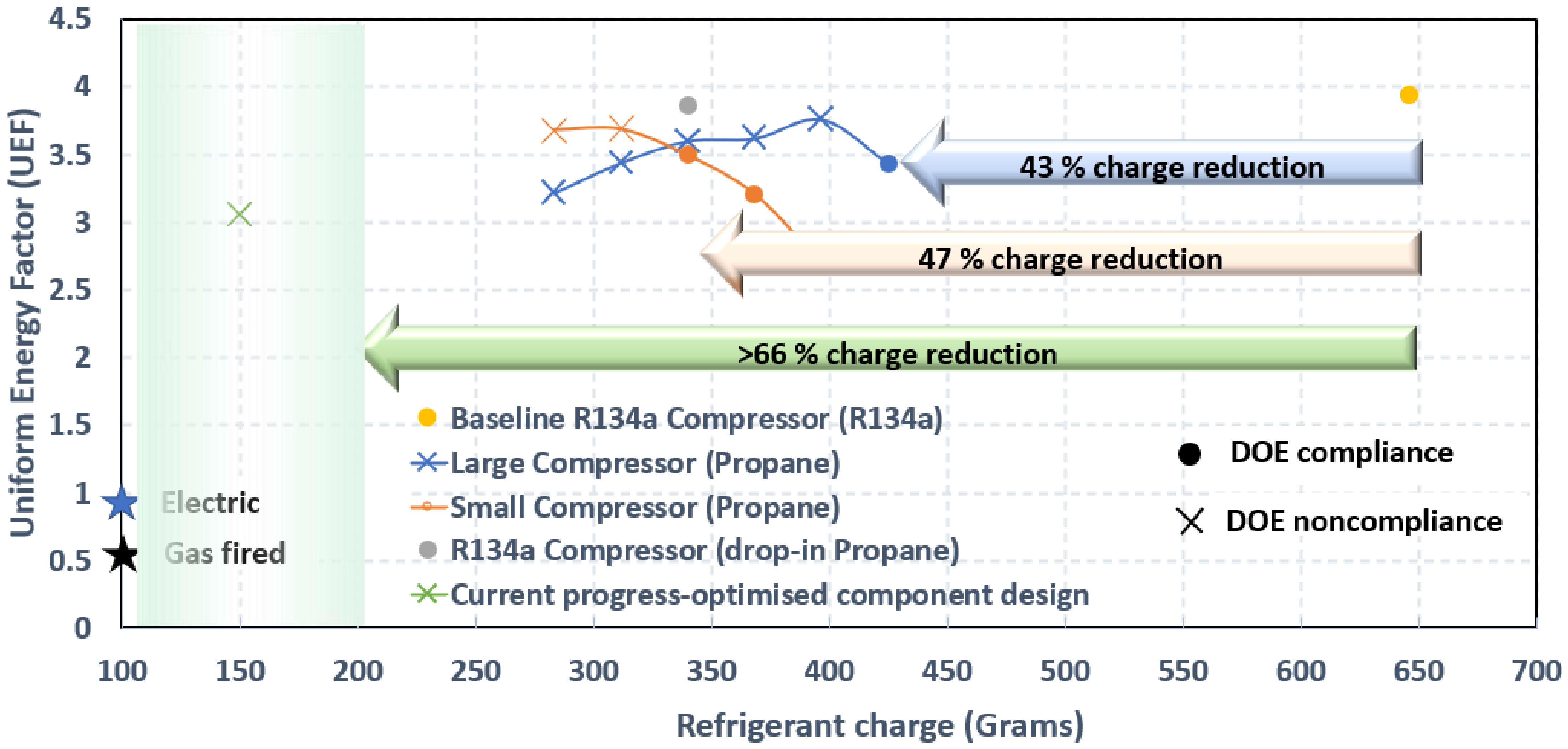
- Refrigerants with higher volumetric capacity
- Component modifications- Design improvement of heat exchangers
- Deployment of improved compressor design
- System modifications- Wrapped vs. split configurations



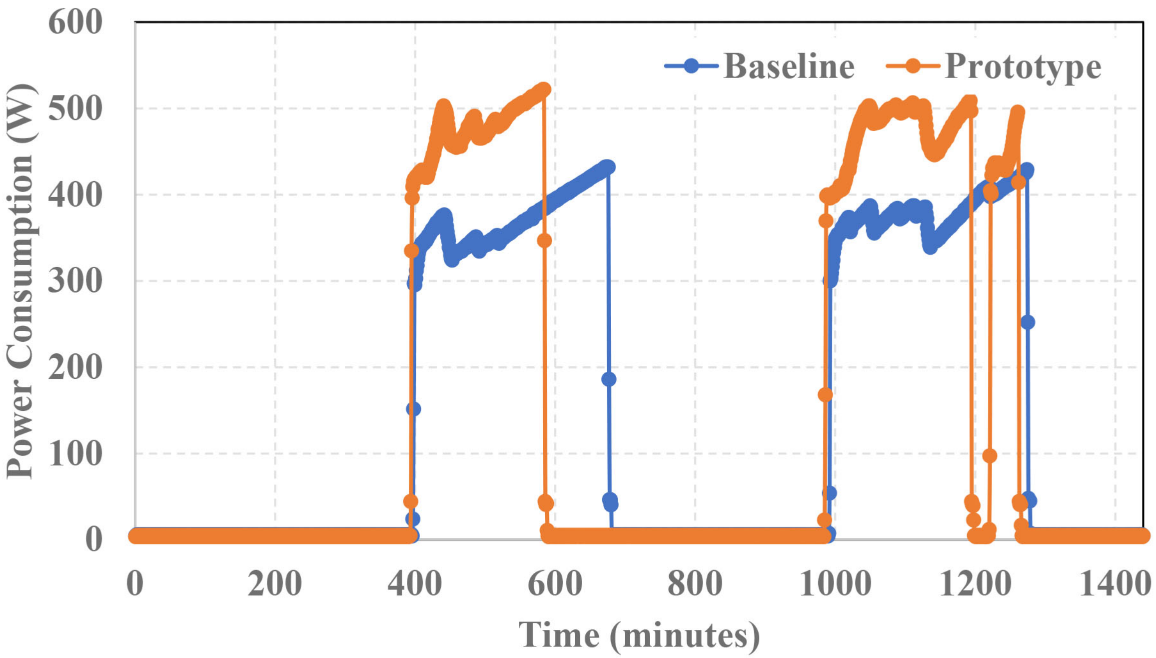


A refrigerants charge less than **150 grams** has been recommended for all indoor applications

Preliminary Developments for Charge Reduction



Field Validation



Power consumption comparison

Field study at Yarnell House- side by side comparison

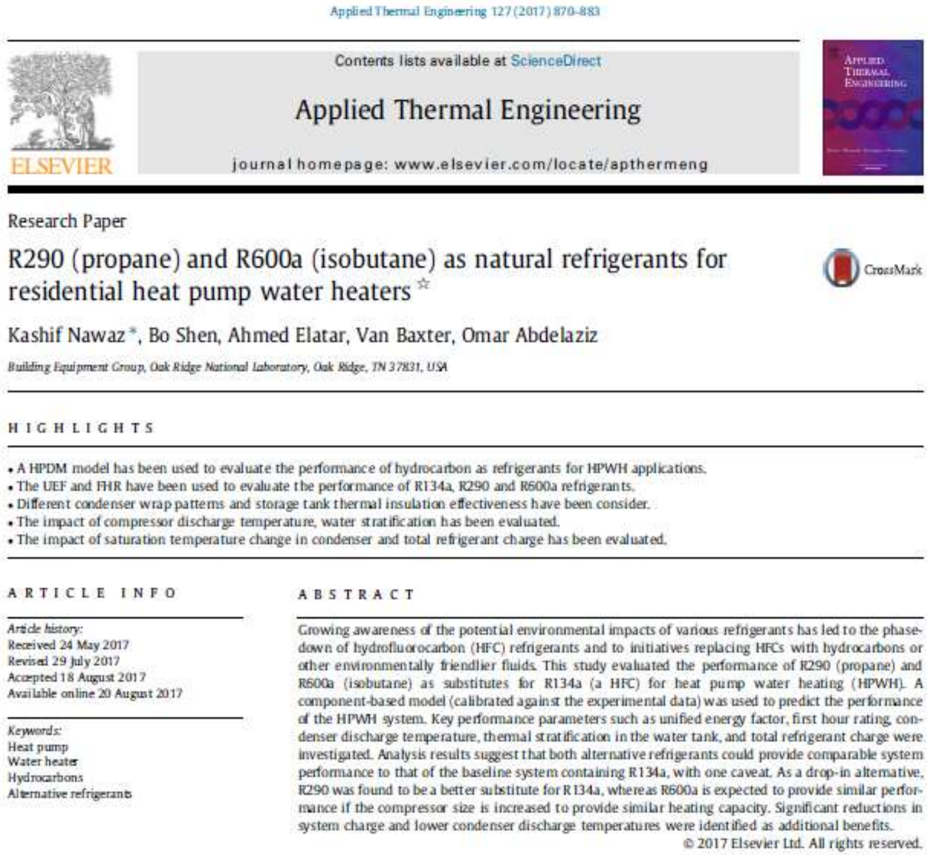
Field evaluation has been in progress for over three months

Conclusions and Future Developments

- R290 (Propane) is a feasible working fluid for residential HPWHs.
- Due to the higher volumetric capacity, direct drop-in-replacement enables a major charge reduction.
- The total refrigerant charge in the system can be further reduced by appropriate component design modifications.
- System level modification is in-progress with a focus on further charge reduction for comparable performance and cost.

Stakeholder Engagement

- DRADA partnership with OEM
- Meetings with experts at technical platform
  - ASHRAE (TC 8.5, TC 1.1)
  - Purdue conferences
- Presentations/Conference papers
  - Five journal articles have been published (ATE, IJR)
  - More than twelve conference papers
  - ACEEE Hot Water Forum



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Research Paper

R290 (propane) and R600a (isobutane) as natural refrigerants for residential heat pump water heaters ☆

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Building Equipment Group, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

HIGHLIGHTS

- A HPDM model has been used to evaluate the performance of hydrocarbon as refrigerants for HPWH applications.
- The UEF and FHR have been used to evaluate the performance of R134a, R290 and R600a refrigerants.
- Different condenser wrap patterns and storage tank thermal insulation effectiveness have been consider.
- The impact of compressor discharge temperature, water stratification has been evaluated.
- The impact of saturation temperature change in condenser and total refrigerant charge has been evaluated.

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ABSTRACT

Growing awareness of the potential environmental impacts of various refrigerants has led to the phase-down of hydrofluorocarbon (HFC) refrigerants and to initiatives replacing HFCs with hydrocarbons or other environmentally friendlier fluids. This study evaluated the performance of R290 (propane) and R600a (isobutane) as substitutes for R134a (a HFC) for heat pump water heating (HPWH). A component-based model (calibrated against the experimental data) was used to predict the performance of the HPWH system. Key performance parameters such as unified energy factor, first hour rating, condenser discharge temperature, thermal stratification in the water tank, and total refrigerant charge were investigated. Analysis results suggest that both alternative refrigerants could provide comparable system performance to that of the baseline system containing R134a, with one caveat. As a drop-in alternative, R290 was found to be a better substitute for R134a, whereas R600a is expected to provide similar performance if the compressor size is increased to provide similar heating capacity. Significant reductions in system charge and lower condenser discharge temperatures were identified as additional benefits.

Thank you

Oak Ridge National Laboratory

Kashif Nawaz, Section Head of Building Technologies Research; Group Leader of Multifunctional Equipment

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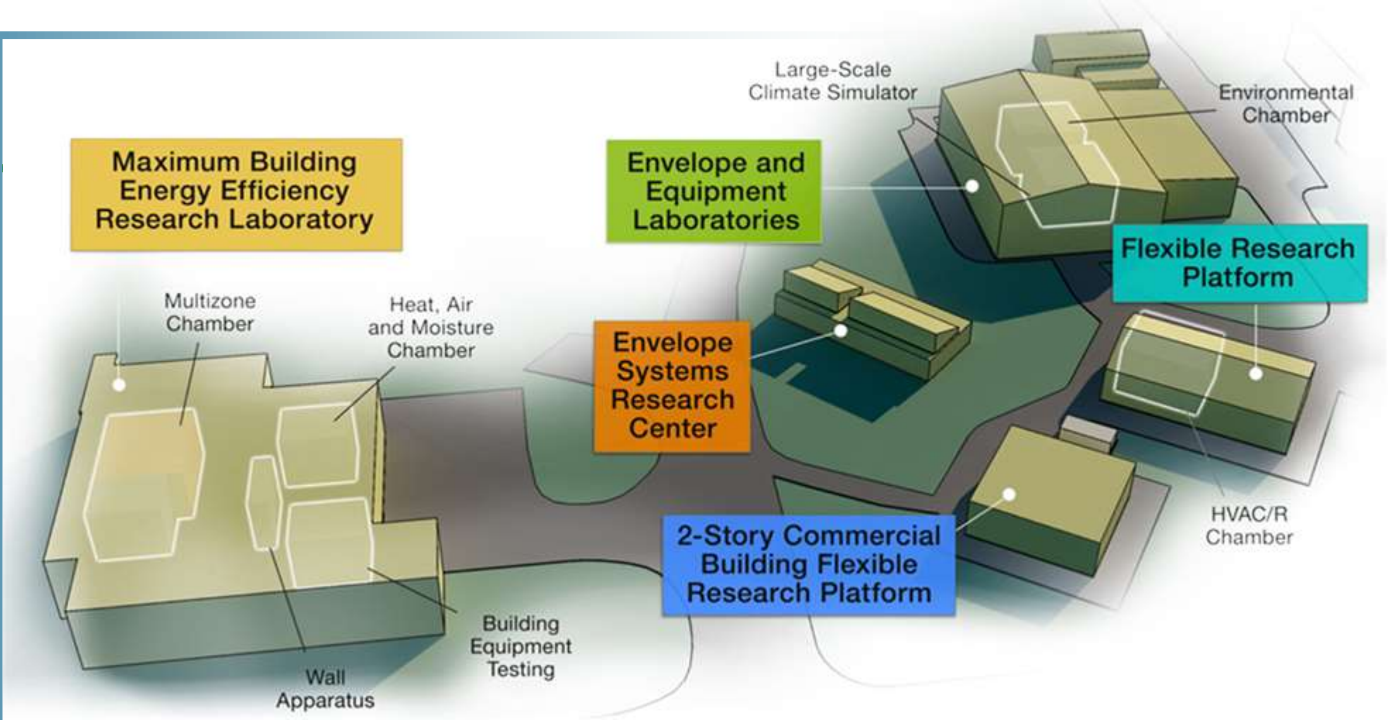

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Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2021				FY2022				FY20ZZ			
Planned budget	30,000				50000							
Spent budget	25,000				55000							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Review of standards for charge requirements												
Performance modeling analysis												
Drop in repalcement evaluation												
Preliminary charge reduction evaluation												
Phase II- CRADA development (in-progress)												

Team

Kashif Nawaz
Project management
Experimentation

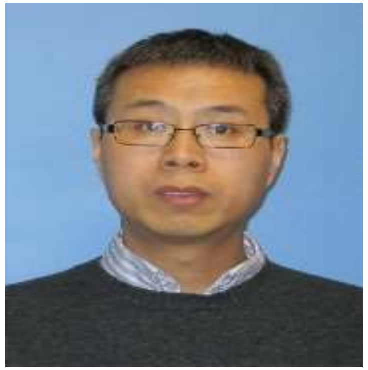
Bo Shen
Performance modeling

Joe Rendall
Prototype development and evaluation

Steve Memory
Prototype development

Jianmin Yin
Prototype development

Ahmed Elatar
Experimentation



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