Next Generation Refrigerants for Domestic Heat Pump Water Heaters

Bo Shen, Mingkan Zhang, Yifeng Hu, Oak Ridge National Laboratory

ABSTRACT

To evaluate next generation refrigerants for domestic heat pump water heaters (HPWHs), we conducted extensive drop-in tests of multiple new refrigerants. For laboratory investigations, we performed drop-in UEF (uniform energy factor) and FHR (first hour rating) tests on two heat pump water heaters; one uses a 220V compressor and 40-gallon water tank and the other uses a 120V compressor and 50-gallon tank. The alternative refrigerants/blends include R-1234yf, R-1234ze, R-515B, R-513A, and R-516A, among which R-513A is A1 (no flame propagation) and the others are A2L (lower flammability). All the alternative refrigerants required similar optimum system charges as the baseline R-134a, and they resulted in similar or better UEFs than R-134a. R-516A produced the highest UEFs in both HPWHs. The resultant discharge temperatures of the new refrigerants/blends are lower than R-134a, indicating good lubricant compatibility. The 120V HPWH delivered > 60 gallons first-hour rating using R-134a. The alternative refrigerants produced lower FHRs due to their smaller volumetric heats of vaporization using the same compressor. Except for R-515B, the other refrigerants/blends delivered FHRs > 60 gallons. Although less impressive than R-516A in terms of UEF and FHR, R-513A could be a suitable option if non-flammability is a priority.

Introduction

In 2015, water heating consumed 19% of source energy in the U.S. residential sector (EIA, 2023, use of energy), making it the third-largest residential end use after space heating and cooling. Electric heat pump water heaters (HPWHs) are a promising replacement for electric resistance water heaters because HPWHs can achieve energy savings of up to 70%. The energy saved is due to the vapor-compression cycle which absorbs heat from ambient or indoor air through an air-to-refrigerant evaporator; a compressor then raises the refrigerant pressure and temperature and rejects high-grade heat to domestic hot water through a condenser. Today, high-efficiency HPWHs have energy factors above 3.3 and can be comparable in source energy consumption to gas water heating. Broader deployment of HPWHs can lead to significant electric energy reduction compared to electric resistance water heaters.

R-134a, a hydrofluorocarbon (HFC) refrigerant, is commonly used for domestic heat pump water heaters. Alternative refrigerants for R-134a include natural refrigerants and synthetic hydrofluoroolefin (HFO) refrigerants.

Natural refrigerants have excellent thermodynamic properties for water heating applications.

Disclaimer
This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

- Propane (R-290): In Direct Expansion Solar Assisted Heat Pumps (DX-SAHP), R290 demonstrates a superior Coefficient of Performance (COP) compared to R-134a and R-1234yf (Duarte 2019).
- Carbon Dioxide (R-744): R-744 is uniquely suited for domestic water heating because its large temperature glide in the gas cooler matches the process of heating water from cold inlet temperatures to high target setpoints (Saikawa 2016). Research into trans-critical R-744 systems shows that blending it with substances like Dimethyl Ether (DME) can significantly reduce optimal heat rejection pressures while maintaining thermodynamic performance (Zhang 2017).

HFO refrigerants offer synthetic alternatives with lower flammability (A2L) compared to pure hydrocarbon refrigerants.

- R-1234yf: Frequently used as a drop-in candidate for R-134a, R-1234yf generally exhibits a slightly lower COP and heating capacity—approximately 11.3% lower than R-290 in solar-assisted configurations—due to its lower enthalpy of vaporization (Duarte 2019).
- R-1234ze(E) and R-1233zd(E): These fluids serve as efficient alternatives for high-temperature water production. R-1233zd(E) can improve the COP relative to older fluids like R-245fa, provided the system includes an internal heat exchanger to manage the suction gas state.
- For alternatives of R-134a with mitigating flammability, manufacturers are actively developing mixtures of HFOs, including R-32 and fire suppression compositions.

For near-term U.S. marketing opportunities, HFO refrigerants and their blends are promising because they offer manageable flammability without conflicting with current manufacturing processes and the existing supply chain. Propane heat pump water heaters (HPWHs) are expected to enter the market, but key challenges include developing compact heat exchangers and reliable leak-detection methods that meet applicable safety regulations. CO_2 systems offer advantages in low-ambient conditions and for high water-heating temperatures (above 140°F). However, most U.S. domestic water heaters are located indoors with typical hot-water supply temperatures around 125°F, where CO_2 systems provide little or no performance benefit while adding significant cost. This study aims to identify short-term opportunities, to drop in alternative refrigerants in the same system without modifications, and to evaluate Uniform Energy Factor (UEF) and First Hour-Rating (FHR). Domestic water heaters, including electric, gas and heat pumps, are generally compared using the three key performance indicators listed below.

24-Hour Uniform Energy Factor:

Water heater efficiencies are rated using 24-hour uniform energy factors (UEF). The procedure requires setting the surrounding air at 67.5°F (19.7°C) temperature and 50% relative humidity. The make-up water temperature is controlled at 58°F (14.4°C). The UEF test procedure starts when the average internal tank temperature reaches 125°F ± 5°F (51.7± 2.7°C), and its water draw profiles vary based on the selected usage pattern.

Typically, a residential water heater is evaluated with the medium water use pattern, which comprises 12 water draws for a total of 55 gallons. The medium use pattern is shown below.

Table 1: Medium Use Draw Pattern

Draw No.	Time during test [hh:mm]	Volume [gallons (liters)]	Flow rate [GPM (L/min)]
1 *	0:00	15.0 (56.8)	1.7 (6.4)
2 *	0:30	2.0 (7.6)	1 (3.8)
3 *	1:40	9.0 (34.1)	1.7 (6.4)
4	10:30	9.0 (34.1)	1.7 (6.4)
5	11:30	5.0 (18.9)	1.7 (6.4)
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 (6.4)
12	17:00	7.0 (26.5)	1.7 (6.4)
Total Volume Drawn Per Day: 55 gallons (208 L)			

* Denotes draws in first draw cluster.

Commercial water heaters are typically evaluating using the high use draw pattern which includes 14 water draws for a total of 84 gallons, as shown below:

Table 2: High Use Draw Pattern

Draw No.	Time during test [hh:mm]	Volume [gallons (liters)]	Flow rate [GPM (L/min)]
1 *	0:00	27.0 (102)	3 (11.4)
2 *	0:30	2.0 (7.6)	1 (3.8)
3 *	0:40	1.0 (3.8)	1 (3.8)
4 *	1:40	9.0 (34.1)	1.7 (6.4)
5	10:30	15.0 (56.8)	3 (11.4)
6	11:30	5.0 (18.9)	1.7 (6.4)
7	12:00	1.0 (3.8)	1 (3.8)
8	12:45	1.0 (3.8)	1 (3.8)
9	12:50	1.0 (3.8)	1 (3.8)
10	16:00	2.0 (7.6)	1 (3.8)
11	16:15	2.0 (7.6)	1 (3.8)
12	16:30	2.0 (7.6)	1.7 (6.4)
13	16:45	2.0 (7.6)	1.7 (6.4)
14	17:00	14.0 (53.0)	3 (11.4)
Total Volume Drawn Per Day: 84 gallons (318 L)			

* Denotes draws in first draw cluster.

In approximation, the UEF is considered as the ratio of the total heat supplied to the tank water during the test to the total power required to operate the system.

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

In the equation above, k represents the individual hot water draw while n represents the total number of draws during the test. Note that n can vary according to the draw pattern used for the test (small, medium and high usage pattern), and M is the total mass drawn for respective draw. T_s, T_i and W_i represent the supply water temperature, inlet water temperature and the total energy consumed by the heat pump (power times the heat pump run time), respectively.

First Recovery Efficiency:

For detailed UEF calculations, the first recovery efficiency is used to correct energy consumption if the actual water temperature rise differs from the standard 67˚F, i.e., from 58°F make up water to 125°F supply water temperature. It can be introduced as a test-derived measure of how efficiently a water heater converts energy into useful heat in the water during the initial recovery period immediately following the simulated-use draws. In practice, it is determined from the same controlled test setup, instrumentation, and outlet-temperature requirements used for the UEF simulated-use test: the procedure creates a defined depletion of stored hot water via the prescribed draw pattern and then evaluates the unit's recovery by comparing the increase in water thermal energy delivered/stored during that first recovery interval against the energy consumed by the heater over the same interval.

First-Hour Rating (FHR):

FHR is a hot-water-delivery/capacity rating, aiming to compare units through a one-hour delivery/recovery period intended to represent high demand while meeting the test's outlet-water-temperature requirement. It is determined from the water tank's storage volume, and the heat pump and supplemental resistance heating capacity. The test procedure starts when an average internal tank temperature reaches 125°F ± 5°F. The hot water is drawn at a 3.0 GPM flow rate (11.4 L/min), and the water draw continues until the supply water temperature drops to 15 degrees [F] below the maximum water supply temperature as observed. The water draw is recovered when the thermostat senses the water temperature rises back to 125°F ± 5°F and terminates again when the water temperature drops by 15R. This process is repeated for one hour. At the end of the hour, if a draw is ongoing, the draw is allowed to complete normally. If a draw doesn't start, a final draw is started and then terminated when the outlet water temperature reaches the same outlet temperature that the previous draw was terminated at.

Alternative Refrigerants/Mixtures

To provide performance comparable to R-134a, alternative refrigerants must have sufficiently high critical temperatures to support heating water over the same temperature range. For direct drop-in applications using similar compressors and heat exchangers, the alternatives should also operate at similar suction and discharge pressures at the required evaporating and condensing temperatures. Table 3 below summarizes the properties of selected alternative refrigerants for R-134a in HPWH applications. All candidate refrigerants have critical temperatures above 90°C, which is adequate for domestic hot water, and they exhibit broadly similar suction and discharge pressures. The volumetric heat of vaporization at 54.4°C and at 4.4°C can be used to compare condensing and evaporating capacity for a given compressor; for a fixed displacement compressor, capacity generally scales with this parameter.

Table 3: Selected Alternative Refrigerants.

Refrigerant	Safety Class	Pressure in Condenser @54.4°C [kPa]	Pressure in Evaporator @ 4.4°C [kPa]	Critical Temperature/Mole weight [C]/[g/mol]	Volumetric Vapor Heat @54.4°C [kJ/m^3]	Volumetric Vapor Heat @ 4.4°C [kJ/m^3]
R-134a	A1	1469	342	101.06/102.0	10959.4	3276.0
R-1234yf	A2L	1444	366	95.0/114.04	10024.4	3263.7
R-1234ze	A2L	1114	254	153.7/114.04	8522.1	2473.2
R-513A	A1	1530	377	96.5/108.43	10832.0	3442.8
R-516A	A2L	1478	369	97.17/102.6	10411.3	3332.5
R-515B	A1	1107	252	108.7/117.48	8472.4	2457.9

Regarding safety classifications, A1 denotes refrigerants with no flame propagation, while A2L denotes lower (but finite) flammability refrigerants. R-513A and R-515B are A1 refrigerants, like R-134a. In addition to the pure refrigerants R-134a, R-1234yf, and R-1234ze, several blends are included: R-513A is a mass-based blend of R-1234yf (0.56) and R-134a (0.44); R-516A is a mass-based blend of R-1234yf (0.775), R-152a (0.14), and R-134a (0.085); and R-515B is a mass-based blend of R-1234ze (0.911) and R-227ea (0.089).

EXPERIMENTAL DROP-IN INVESTIGATIONS

Two Heat Pump Water Heaters for Refrigerant Drop-In Investigations

Two residential HPWHs are evaluated for refrigerant drop-in investigations in ORNL's appliance chamber. One HPWH unit uses a 220 V, single-phase compressor with a rated capacity of 4 kBtu/hr; the other HPWH is a recently introduced model that uses a 120 V compressor with a rated capacity of 12 kBtu/hr. The 220 V HPWH is paired with a 40-gallon water tank and includes two electric resistance elements (top and bottom). The top element provides supplemental resistance heating and largely determines the unit's first-hour rating (FHR). The 120 V HPWH is paired with a 50-gallon water tank and has no resistance heaters; its heating capacity is provided solely by the 120 V, 12 kBtu/hr compressor.

Experimental Instrumentations

Figure 1 below illustrates the laboratory instrumentation, which was similar for both the HPWHs.

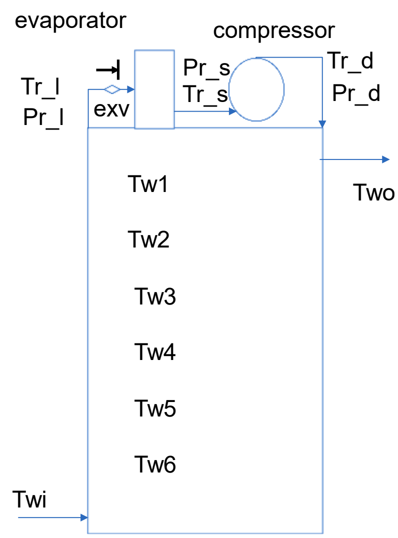


Figure 1. Laboratory Instrumentations.

Instrumentations: Power: total power measurement including compressor and fan. Refrigerant pressures (*Pr*): suction (*Pr_s*), discharge (*Pr_d*) and liquid (*Pr_l*), which were measured for the 220V, 40-gallon HPWH only. Refrigerant temperatures (*Tr*): suction (*Tr_s*), discharge (*Tr_d*) and liquid (*Tr_l*). Water temperatures (*Tw*): six thermocouple tree; entering water temperature (*Twi*) and leaving water temperature (*Two*). A water mass flow meter measured the water draws at the make-up water side. The water draw patterns for medium and high uses, and the logic for FHR tests were programmed in LabVIEW, which monitored 24-hour UEF tests and FHR tests.

Experimental Results of 220V, 40-Gallon HPWH

We tuned the system charge for each refrigerant to reach an optimal UEF at the medium use draw pattern. Figure 2 below presents the optimized charges of the individual refrigerants/blends. All tested refrigerants require higher or equal charge to R-134a.

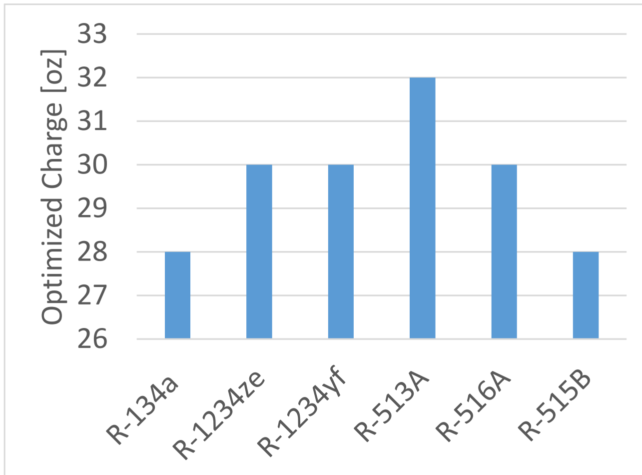
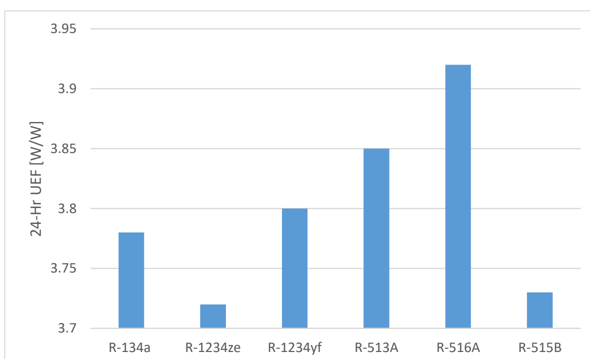


Figure 2. Optimized System Charges, 220V, 40-Gallon HPWH.

Figure 3 below presents measured optimum 24-hour UEFs at the medium use draw pattern. Our laboratory measured UEF of the baseline R-134a matched the manufacturer's nameplate value very closely, i.e., 3.78 versus 3.75. This alignment suggests that the laboratory setup and gathered data were comparable to manufacturer tests. Measured UEFs for replacement refrigerants ranged from 3.72 to 3.92, indicating only a small deviation from the baseline R-134a UEF.



Refrigerant	R-134a (baseline)	R-1234ze	R-1234yf	R-513A	R-516A	R-515B
Charge [oz]	28	30	30	32	30	28
24-Hour UEF [W/W]	3.78 (nameplate: 3.75)	3.72	3.80	3.85	3.92	3.73

Figure 3. Optimized UEFs, 220V, 40-Gallon HPWH.

Figure 4 below illustrates the compressor run time during the 24-hour UEFs tests. The compressor run time tends to be opposite to the volumetric vapor heat, i.e., refrigerant latent heat during evaporating and condensing, as given in Table 3. The run time, required within 24-hour UEF period to deliver a similar level of thermal energy, indicates heating rate from the vapor compression system. Smaller volumetric vapor heat of one refrigerant in a fixed size of compressor leads to reduced heating capacity and thus longer heating time.

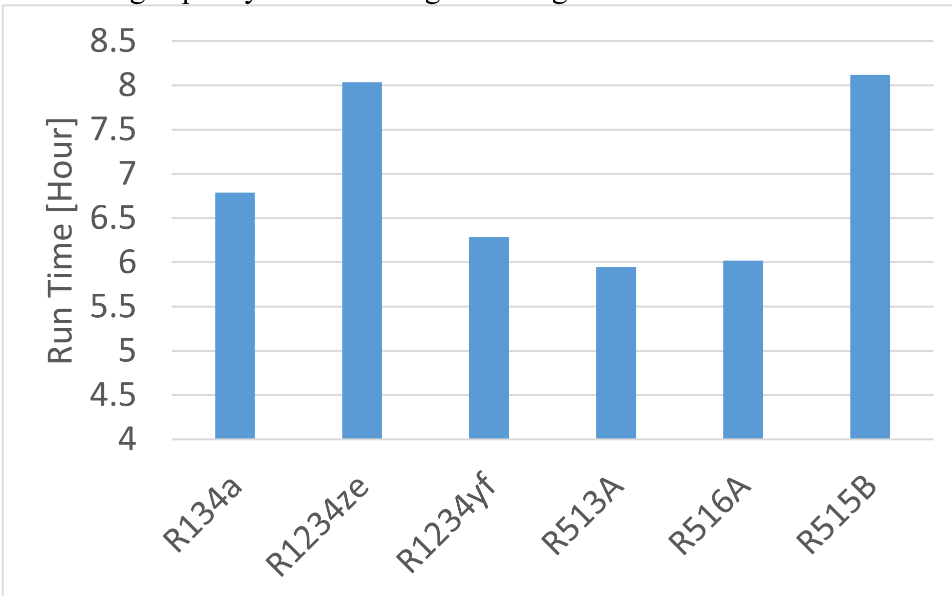


Figure 4. Compressor Run Periods during 24-Hour UEF Tests, 220V, 40-Gallon HPWH.

Figure 5 below presents the maximum compressor discharge temperatures of various refrigerants during 24-hour operation. All the alternative refrigerants resulted in lower discharge temperatures compared to R-134a, indicating good lubricant compatibility.

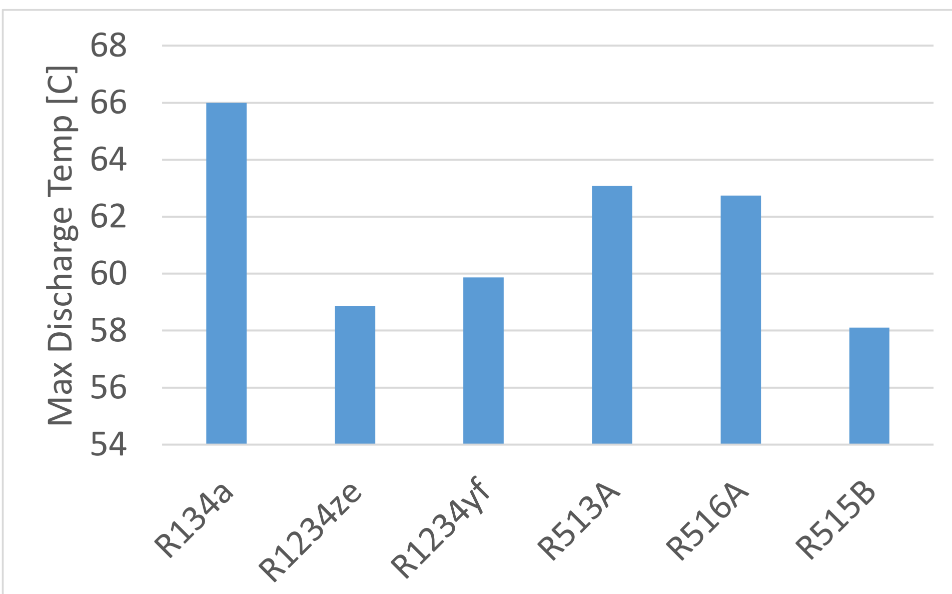


Figure 5. Compressor Maximum Discharge Temperatures, 220V, 40-Gallon HPWH.

Experimental Results of 120V, 50-Gallon HPWH

We tuned system charges of the 120V, 50-gallon HPWH to reach optimal UEFs at the medium draw pattern. Figure 6 below illustrates the optimized refrigerant charges. In comparison to the

220V, 40-gallon HPWH, the 120V HPWH has much larger evaporator and condenser to accommodate the larger compressor, that requires much larger refrigerant mass. R516A's charge is lower for the 120V system but higher for the 220V unit, which could be due to the different compressors.

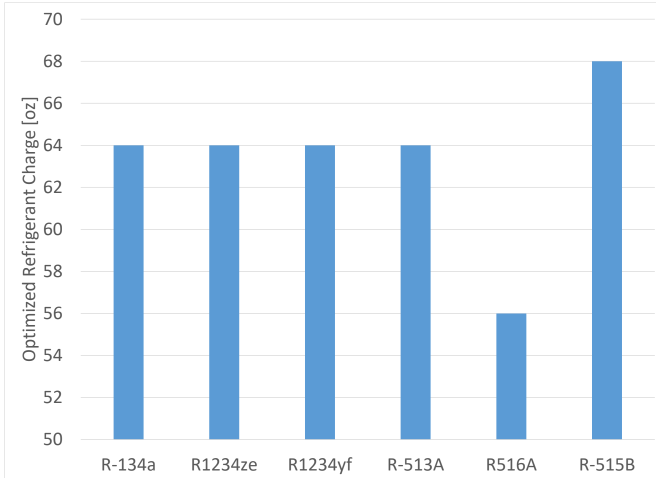


Figure 6. Optimized System Charges, 120V, 50-Gallon HPWH.

The UEF tests were performed at both the medium draw and the high draw patterns. Figure 7 below illustrates the measured 24-hour UEFs. The UEF at the high draw of each refrigerant is always higher than that at the medium draw, because larger water draw volume resulted in lower average water tank temperature and refrigerant condensing temperature. The relative trends at the two draw patterns are consistent among the refrigerants. All the alternative refrigerants led to higher UEFs than R-134a.

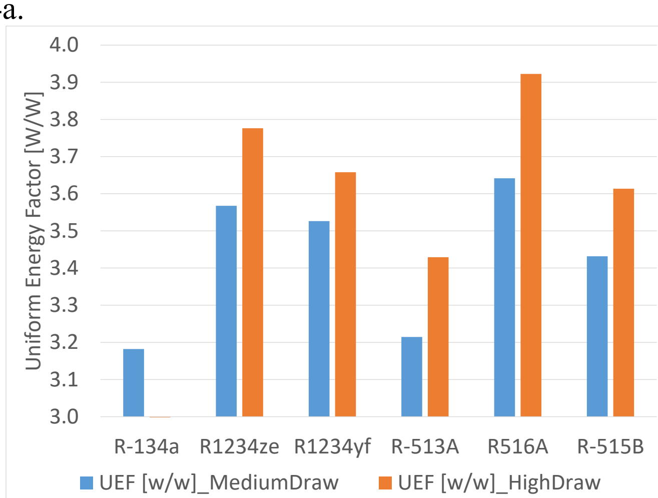


Figure 7. Optimized UEFs, 120V, 50-Gallon HPWH.

Figure 8 below presents measured FHRs. These values were dictated by the refrigerant vaporization heat, due to using the same compressor and no resistance heaters. All the alternative refrigerants resulted in slightly lower FHRs, consistent with the thermophysical properties given in Table 3.

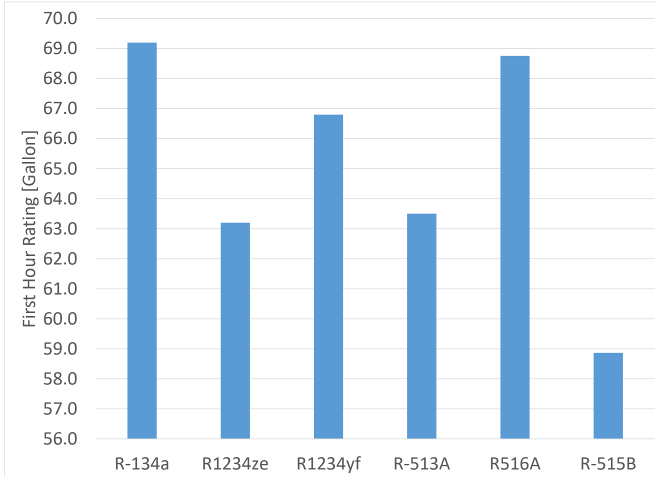


Figure 8. First Hour Ratings, 120V, 50-Gallon HPWH.

Table 4 below summarizes all the experimental results of the 120V, 50-gallon HPWH.

Table 4. Experimental Results of 120V. 50-Gallon HPWH.

	R-134a	R1234ze	R1234yf	R-513A	R516A	R-515B
Optimized Charge [oz]	64	64	64	64	56	68
UEF [w/w]_Medium Draw	3.18	3.57	3.53	3.21	3.64	3.43
UEF [w/w]_High Draw	N/A	3.78	3.66	3.43	3.92	3.61
FHR [gallon]	69.2	63.2	66.8	63.5	68.8	58.9

Summary

This study evaluates next-generation refrigerants in domestic heat pump water heaters (HPWHs), focusing on near-term "drop-in" options that require minimal redesign. Oak Ridge National Laboratory conducted extensive laboratory testing on two residential HPWH platforms: a 220V unit with a 40-gallon tank and resistance backup elements, and a 120V unit with a 50-gallon tank and no resistance heat (heat pump only). Candidate refrigerants/blends included R-1234yf, R-1234ze, R-515B, R-513A, and R-516A. Of these, R-513A and R-515B are A1 (no flame propagation) while the others are A2L (lower flammability).

Performance was assessed primarily using Uniform Energy Factor (UEF) from standardized 24-hour tests (medium and, for the 120V unit, high draw patterns) and First-Hour Rating (FHR) to measure hot-water delivery capability under heavy demand. For each refrigerant, the team optimized charge level to maximize UEF. A key practical finding is that all alternatives required refrigerant charges similar to R-134a.

Across both HPWHs, the alternative refrigerants delivered UEF equal to or better than R-134a, with R-516A producing the highest UEFs in both platforms. In addition, compressor discharge temperatures were lower than with R-134a for all alternative candidates, which the authors interpret as a positive indicator for lubricant compatibility and compressor operating robustness. For the 120V heat-pump-only unit, the baseline R-134a achieved ~69 gallons FHR, while most alternatives produced slightly lower FHR—consistent with their lower volumetric heat of vaporization when using the same fixed-displacement compressor. Importantly, all alternatives except R-515B still exceeded 60 gallons FHR, indicating that capacity remained broadly acceptable despite modest reductions.

Overall, the results identify R-516A as the best-performing drop-in candidate when prioritizing maximum efficiency and strong hot-water delivery. If nonflammability (A1) is a primary constraint, R-513A emerges as a practical compromise: it does not match R-516A's top performance but still provides competitive efficiency with acceptable FHR, making it a credible near-term replacement option for manufacturers seeking to minimize flammability concerns while improving or maintaining performance relative to R-134a.

ACKNOWLEDGEMENT

The authors would like to acknowledge the funding and support provided by the US Department of Energy, Building Technologies Office, through Dr. Wyatt Merrill, Technology Manager of HVAC, WH and Refrigeration. The authors would also like to thank the Rheem engineering team, led by Mr. Ati Manay in collaboration and supervising this work.

References

Duarte, W.M., Paulino, T.F., Pabon, J.J., Sawalha, S., Machado, L. (2019). Refrigerants selection for a direct expansion solar assisted heat pump for domestic hot water. Solar Energy, 184, 527–538.

Energy Information Administration, EIA, (2023), use of energy, https://www.eia.gov/energyexplained/use-of-energy/homes.php

Saikawa, M., Koyama, S. (2016). Thermodynamic analysis of vapor compression heat pump cycle for tap water heating and development of CO2 heat pump water heater for residential use.

Zhang, X., Wang, F., Liu, Z., Gu, J., Zhu, F., Yuan, Q. (2017). Performance Research on Heat Pump Using Blends of R744 with Eco-friendly Working Fluid. Procedia Engineering, 205, 2297–2302.