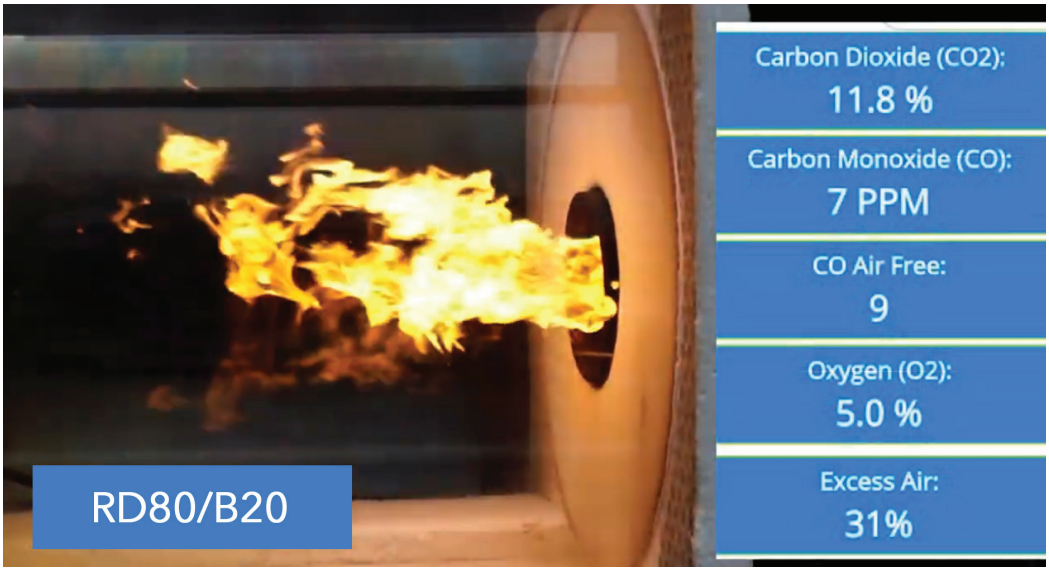
Field Study: Conversion of Oil-Fired Heating Systems to 100% Renewable Fuel

August 2026



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NORA
Advancing Liquid Fuel Home Heating

Field Study:
Conversion of Oil-Fired
Heating Systems to 100% Renewable Fuel

August 2026

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The National Oilheat Research Alliance (NORA) was authorized by Congress in 2000 to advance the liquid heating fuels industry and benefit American consumers. NORA supports research and development, professional education and technician training, consumer education, and programs that improve energy efficiency, safety, reliability, and carbon reduction. Working with state and regional associations, manufacturers, fuel marketers, researchers, and other industry partners, NORA advances innovative fuels, technologies, and practices that support efficient, dependable, and lower-carbon heating and hot water.

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Preface

For generations, heating oil has kept millions of American homes warm through the coldest winters. It has earned a reputation for reliability, affordability, and performance. Yet while many people still view heating oil as a traditional petroleum fuel, the industry behind it has been anything but static.

Over the past 25 years, the liquid heating fuels industry has undergone one of the most significant transformations in its history. It has invested in cleaner fuels, more efficient appliances, renewable energy technologies, robust technician training, and groundbreaking research—all while continuing to deliver dependable heat to millions of homes. The story of Oilheat is not about standing still. It is about constant evolution.

At the start of the 2000s, conventional heating oil contained between 2,000 and 5,000 parts per million (ppm) of sulfur. While it heated homes effectively, its sulfur content contributed to emissions, heating appliance fouling, and increased maintenance requirements.

Recognizing the opportunity for improvement, liquid heating fuel marketers, refiners, heating appliance manufacturers, regulators, and the National Oilheat Research Alliance (NORA) worked together to dramatically reduce sulfur content.

Between 2010 and 2018, Northeastern states gradually adopted ultra-low-sulfur heating oil (ULSHO), reducing sulfur levels to just 15 ppm.

The result was remarkable:

- More than a 99% reduction in sulfur content
- Significant reductions in sulfur dioxide and particulate emissions
- Cleaner-burning fuel
- Longer heating appliance life
- Lower maintenance costs for homeowners

This was not simply a regulatory achievement; it was one of the largest environmental improvements ever made to residential liquid heating fuels.

While sulfur levels were falling, another innovation was beginning to take shape, and researchers started asking a simple question:

Could biodiesel become part of the future of home heating?

Answering that question would require years of scientific research. Beginning in the early 2000s, NORA and the National Biodiesel Board (now CFAA) partnered with heating appliance manufacturers, universities, Brookhaven National Laboratory, liquid heating fuel marketers, and the biodiesel industry to evaluate biodiesel blends in residential heating systems.

The research examined the factors most important to reliability, safety, and performance:

- Burner performance
- Fuel stability
- Cold-weather operation
- Storage characteristics
- Emissions
- Materials compatibility
- Long-term reliability

The goal was not simply to prove that biodiesel worked; it was to prove that it worked every day, every winter, in every type of heating system.

Research alone does not change an industry; strict standards do. For the inclusion of renewable, low-carbon fuels in the liquid heating fuel stream, the turning point came through ASTM International, whose fuel specifications define the quality and performance standards trusted throughout the energy industry.

In 2002, ASTM established ASTM D6751, creating a national specification for B100 biodiesel. Six years later came an even bigger milestone: ASTM D396, the national specification for heating oil, was revised to recognize biodiesel blends up to B5. That decision changed everything.

Bioheat® fuel, the brand name for the blended fuel, was no longer considered experimental; it had become part of the heating oil industry's accepted fuel standard. Over the next decade, research continued. NORA, NBB, heating appliance manufacturers, ASTM committees, and other industry partners expanded testing through B20, culminating in the adoption of specifications for B6 through B20 in 2014. This work evaluated fuel quality, combustion performance, emissions, storage stability, cold-flow characteristics, and long-term heating appliance durability, laying the groundwork for today's higher renewable fuel blends.

Most recently, ASTM standards have continued to expand to support B50 Bioheat® fuel applications, with the adoption of specifications for B21 through B50 in April 2026. At the same time, manufacturers have introduced UL-listed burners and boilers rated to operate on B50 and, in some cases, B100, creating a clear pathway toward renewable liquid heating without requiring homeowners to replace their existing heating systems. The message is clear: the science came first, standards followed, and markets grew.

While the Northeast was proving that biodiesel could reliably heat homes, California was demonstrating how low-carbon fuels could be valued through market-based policy. The adoption of the California Low Carbon Fuel Standard (LCFS) in 2009 fundamentally changed the economics of renewable fuels by rewarding reductions in lifecycle carbon intensity rather than prescribing a specific technology. Together, ASTM standards in the heating market and California's LCFS in the transportation market created two complementary forces that accelerated investment in biodiesel, renewable diesel, and the broader renewable fuels industry.

Produced from feedstocks similar to those used for biodiesel, renewable diesel has experienced significant growth in both production and adoption, especially from 2015 to the present, with U.S. volumes now exceeding 3 billion gallons annually. As adoption grew, blends of renewable diesel and biodiesel became increasingly common. The favorable molecular properties of the two fuels helped improve the economics of producing a fully renewable liquid transportation fuel.

As renewable diesel continued to grow on a commercial scale, NORA recognized an opportunity to evaluate its performance in liquid fuel heating applications, both as a standalone fuel and in blends with biodiesel. Researchers at the NORA Research and Education Center in Plainview, Long Island, tested these fuels in a variety of existing heating systems. After several years of successful laboratory and controlled testing, NORA determined that a large-scale field demonstration was the next critical step in assessing their readiness for residential and commercial use.

This led to the development of the *NORA Field Study—Conversion of Oil-Fired Heating Systems to 100% Renewable Fuel*, designed to assess real-world use and performance under diverse conditions. The study included 121 sites across the Commonwealths of Pennsylvania and Massachusetts. The following report presents the data and findings from this two-heating-season field evaluation.

Michael Devine, President
National Oilheat Research Alliance

Abstract

The use of renewable liquid fuels as an alternative to No. 2 heating oil has steadily increased in recent years. The most widely adopted of these renewable fuels are biodiesel (BD) and renewable diesel (RD). Several laboratory studies have confirmed the feasibility of using these fuels in existing heating systems, as well as material compatibility with legacy heating components. Market adoption of blends of these fuels, in both residential and commercial applications, has become widespread, with increasing blend levels. Driven by the liquid heating fuels industry's commitment to reducing fossil fuel use, along with evolving federal, state and local policies, a future powered by 100% renewable liquid heating fuels may be closer than ever.

NORA's Field Study—Conversion of Oil-Fired Heating Systems to 100% Renewable Fuel details the results of an 18-month field study on the use of drop-in, 100% renewable liquid fuels in 121 heating appliances in buildings in Pennsylvania and Massachusetts. The fuels include blends of 50% RD with 50% BD (RD50/B50) and 80% RD with 20% BD (RD80/B20) by volume. Test sites were selected to include a broad range of heating appliance types currently in use, including boilers, furnaces, and water heaters. Fuel storage tanks were not replaced, emptied, or cleaned prior to the start of deliveries of the test fuel. No oil burner or fuel system changes were made prior to the test. At four sites, the burner primary controls were upgraded to accommodate the lower luminosity of the RD and BD flames.

Sites were divided into Level 1 (28 sites) and Level 2 (93 sites). Level 1 sites were visited five times during the project for inspection, combustion testing, and fuel sampling. Combustion performance with the test fuel blends was within specifications based on smoke number, excess air, and CO measurements with the exception of three sites. Corrective measures were taken and the issues did not recur. Burners were not systematically retuned as part of the initial conversion; selected adjustments were made later during service or testing. When comparing burner service statistics before and after conversion to the test fuels, no increase in service requirements was found.

NORA created a visual numerical scale to evaluate burner head coking. Higher rates of head coking were found in "cold chamber" appliances, which have no refractory lining in the combustion chamber. With "hot chamber" appliances, those with a refractory lining, nominal head coking was observed. If burners are serviced in accordance with manufacturers' instructions, no long-term head coking concern is expected.

An estimated 275,000 gallons of test fuels were delivered to the test sites throughout the duration of testing.

Acknowledgments

The successful completion of this study relied on collaboration among many industry parties. The NORA team would like to extend its gratitude to each one of them, starting with the co-sponsor, Clean Fuels Alliance America (CFAA), whose supplemental funding of this project was instrumental. A special token of appreciation is due to Chevron for supplying the fuel, especially to Jason Lawrence, whose vision for the industry was, in part, responsible for kick-starting the project and its continuation.

We acknowledge the technical insight and guidance provided by burner manufacturers R.W. Beckett Corp. and Carlin Combustion Technology Inc., which added to the robustness of this study.

We would also like to thank the service companies Cubby Oil & Energy, D.E. Duffey and Sons, Moyer & Son Inc., Noonan Energy Corp., Oehlert Bros. Inc., Rhoads Energy, Shipley Energy, and Wilson Oil & Propane. Their commitment to obtaining and retaining the study sites, delivering fuel to the locations, and accommodating Level 1 site visits throughout the study period was instrumental in our endeavors.

Gratitude also goes to Broco Energy, Rhoads Energy, and Oehlert Bros. Inc. for storing and supplying fuel in the Massachusetts, Southeastern Pennsylvania, and South-Central Pennsylvania regions, respectively.

We are deeply grateful to the individual service managers and technicians from each of the service companies who ensured that the test sites were serviced properly and accompanied the team to Level 1 site visits.

Last but not least, the NORA team would like to show its utmost appreciation to the home and business owners who agreed to have the test fuel delivered to their homes or businesses and allowed the research team to perform site visits.

Table of Contents

Preface i
Abstract iii
Acknowledgments iv
List of Figures vi
List of Tables vi
Definitions viii
Introduction 1
Methods 4
- Site Selection 4
- Appliances and Burners 4
- Fuel Storage and Usage 5
- Service and Delivery Data 6
- Site Level Designations 7
- Analysis of Fuel Samples 9

Results 12
- Service Data 12
- Analysis of Collected Fuel Samples 13
  - Biodiesel Content 13
  - Oxidative Stability 15
  - Total Acid Number (TAN) 16
  - Bound Water Content 17
  - Water and Sediment 17
  - Biological Contamination 19
- Density 20
- Viscosity 20
- Head Coking 21
  - Hot Chamber Boilers 22
  - Cold Chamber Boilers 23
  - Furnaces 24
  - Water Heaters 25

Discussion 26
Conclusions 28
References 30

Appendix A. Certificates of Analysis of the Test Fuels Used for Making Blends 31
Appendix B. Burner Head Coking Scales 33
Appendix C. Fuel Testing Data 35
Appendix D. Biodiesel Content Change Between Visits 1 and 2 43

List of Figures

Figure 1. Map showing all locations used in the study. 4
Figure 2. Example of fuel collection container (left) and a middle tank fuel sample (right)..... 9
Figure 3. Biodiesel content change between Visits 1 and 2, showing the sites reaching the desired biodiesel levels. 15
Figure 4. Photos: retention heads from Level 1 sites with hot chamber boilers during visit period 5. 22
Figure 5. Photos: retention heads from select Level 2 sites with hot chamber boilers during visit period 5. 23
Figure 6. Photos of the retention heads from all sites with cold chamber boilers during visit period 5. 23
Figure 7. Photos: retention heads from Level 1 sites with furnaces during visit period 5..... 24
Figure 8. Photos: retention heads from Level 2 sites with furnaces during visit period 5 24
Figure 9. Photos: retention head from sites with water heaters during visit period 5. 25
Figure 10. Average head coking grades for each appliance type from Visit 5 25

Figure B1: Examples of retention heads with a rating of 0..... 32
Figure B2. Examples of retention heads with a rating of 1..... 32
Figure B3. Examples of retention heads with a rating of 2..... 32
Figure B4. Examples of retention heads with a rating of 3..... 33
Figure B5. Examples of retention heads with a rating of 4..... 33
Figure B6. Examples of retention heads with a rating of 5..... 33

List of Tables

Table 1. Basic Properties of BD and RD 1
Table 2. List of the Participating Liquid Heating Marketers 4
Table 3. Distribution of Test Sites 5
Table 4. Distribution of Burner Manufacturers 5
Table 5. Age Distribution of Fuel Tanks in the Study 6
Table 6. Level 1 Test Sites 8
Table 7. Level 1 Site Visit Periods..... 8
Table 8. Biodiesel Content Measured at Each Site Across the Five Site Visits 14
Table 9. Number of Samples with Oxidative Reserve At Least 6 Hours 15
Table 10. Average, Standard Deviation, Minimum and Maximum Values Measured for Oxidative Reserve at Each Visit..... 16
Table 11. Number of Samples with TAN Less Than or Equal to 0.3 mg KOH/g 16

Table 12. Average, Standard Deviation, Minimum and Maximum Values Measured for TAN at Each Visit 16
Table 13. Average, Standard Deviation, Minimum and Maximum Bound Water Content Measured on Each Visit 17
Table 14. Water and Sediment at Each Site Over Five Site Visits 18
Table 15. Presence of Water Heat Map 18
Table 16. Number of Samples with Visible Water at the Bottom 18
Table 17. Measured Biological Activity at Selected Sites 19
Table 18. Average, Median, Minimum, and Maximum Biological Activity 19
Table 19. Average, Standard Deviation, Minimum and Maximum Density @ 15 °C Measured on Each Visit 20
Table 20. Average, Standard Deviation, Minimum and Maximum Kinematic Viscosity @ 40 °C Measured on Each Visit 20

Definitions

ASTM: ASTM International, formerly American Society for Testing and Materials.

Biodiesel (BD): Biodiesel is a renewable, biodegradable fuel manufactured from vegetable oils, animal fats, or recycled restaurant grease. It meets both the biomass-based diesel and overall advanced biofuel requirement of the *Renewable Fuel Standard* and its properties are specified in ASTM D6751. It is often blended with No. 2 heating oil for space heating applications.

Bioheat® fuel: A blend of ultra-low sulfur No. 2 heating oil and renewable biodiesel made from organic and recycled materials, such as soybean oil, algae, and used cooking grease.

Cad cell: A flame sensing device commonly used in liquid fuel burners in the US, also known as a cadmium sulfide cell. The cadmium sulfide in the device produces low resistance when exposed to visible light and high resistance under dim or no lighting conditions.

cATP: The concentration of adenosine triphosphate, a molecule important to living cells. It is present in all living materials and can be used to track bacterial and fungal growth in liquid fuels.

Cold chamber appliances: Appliances with no refractory lining in the combustion chamber; typically known as triple pass boilers for their heat exchanger design.

Head coking: Fouling of the burner retention head and other combustion chamber facing components caused by unburnt fuel.

Hot chamber appliances: Appliances that have refractory lining covering the combustion chamber; typically known as single-pass or pin type boilers, warm air furnaces and direct fired water heaters.

Liquid fuel marketer: A company that delivers liquid home heating fuel to end users. The fuels may be No. 2 heating oil, biodiesel and renewable diesel blends, or kerosene. They frequently operate a heating system service and/or installation department.

No. 2 heating oil: A middle-distillate dyed fuel used primarily in residential and light commercial boilers, furnaces, and water heaters. It is produced and sold for heating applications and must meet ASTM D396 specifications. Between 2010 and 2018, Northeastern states gradually adopted ultra-low sulfur heating oil (ULSHO), reducing sulfur levels to 15 ppm.

Oxidative reserve: A measure of stability and resistance to degradation of fuels from oxygen exposure over time. B20 ASTM D396 specifies an oxidative reserve of a minimum of six hours.

Renewable diesel (RD): Renewable diesel is a fuel made from fats and oils, such as soybean oil or canola oil, and through catalytic hydrogenation, is processed to be chemically the same as petroleum diesel. It meets the ASTM D975 and D396 specifications for petroleum in the United States.

Retention head: A burner component installed at the end of a burner air tube that allows precise air flow to accommodate efficient combustion.

Total Acid Number (TAN): A measurement of acidity that is determined by the amount of potassium hydroxide in milligrams that is needed to neutralize the acids in one gram of fuel. It is an important parameter in determining fuel stability. B20 ASTM D396 allows a maximum of 0.3 mg KOH/g.

Introduction

Biodiesel (BD) is a renewable fuel produced from vegetable oils, waste fats and greases using a transesterification process (McCormick and Moriarty 2023). It is often described as a fatty acid methyl ester (FAME). Relative to No. 2 heating oil, it has an elevated oxygen content and slightly reduced heating value.

Renewable diesel (RD), also a renewable fuel and alternatively known as hydrotreated vegetable oil (HVO), is produced from the same feedstocks using a different process. At elevated pressure and temperature, the feedstock oil is combined with hydrogen and passed over a catalyst. In this process, oxygen is removed, leading to a fuel with a higher heating value than biodiesel. Because of the higher pressure and temperature and the need for hydrogen and the catalyst, RD is more costly to produce than BD. Table 1 provides a summary of key combustion-related properties of both of these fuels, relative to No. 2 heating oil.

Table 1. Basic Properties of Petroleum No. 2 Heating Fuel, Biodiesel and Renewable Diesel

Property	Units	Petroleum No. 2 Heating Fuel	FAME Biodiesel	HVO Renewable Diesel
Carbon	wt%	87	77	85
Hydrogen	wt%	13	12	15
Oxygen	wt%	0	11	0
Higher Heating Value	Btu/gallon	139,000	125,300	132,800
Density	lb/gallon	7.1	7.3	6.5
Distillation *temperature for 90% recovered*	°F	640	680	<563
Pour Point	°F	-31 to +5	23 to 50	-40 to 15
Flash Point	°F	140-176	212-338	>158
Kinematic viscosity	mm^2/s @ 40 °C	1.9/4.1 min/max	1.9/6.0 min/max	2.8 typical
Aromatics	%	20-35	0	0

The required properties of biodiesel are defined in the ASTM D6751 standard. The feedstock from which biodiesel is made is not considered to be a part of the commercial description of this fuel and it is common in the industry to produce biodiesel using a combination of multiple feedstocks. Only the final properties relative to the ASTM D6751 specification are important. Assuming a carbon intensity for petroleum No. 2 oil of 95 gCO2e/MJ, the reduction in carbon intensity for the RD80/B20 blend and the RD50/B50 blend is estimated at 76.5% and 77.5% respectively, based on the feedstocks used.

Properties of heating fuels are prescribed in the ASTM D396 standard. Blends of up to 5% biodiesel in heating oil are effectively considered equivalent to traditional No. 2 heating oil. Blends of up to 20% biodiesel in heating oil have a separate designation in this standard but are fully defined. A modification to the D396 standard to include up to 50% biodiesel blends was approved and published in April 2026.

Renewable diesel is an “oxygen-free” hydrocarbon and meets the definitions and property

specifications for No. 2 heating oil in the D396 standard. There is no separate specification for RD as a heating fuel. From the production process, RD has a near-zero aromatics content and is sometimes referred to as a paraffinic heating fuel. In some applications, notably diesel engines, aromatics are associated with increased particulate emissions. Both RD and BD are fully miscible with traditional fossil No. 2 heating oil.

Since 2002, work has been conducted to test and demonstrate the potential for use of biodiesel blends in heating applications (NORA n.d.), including:

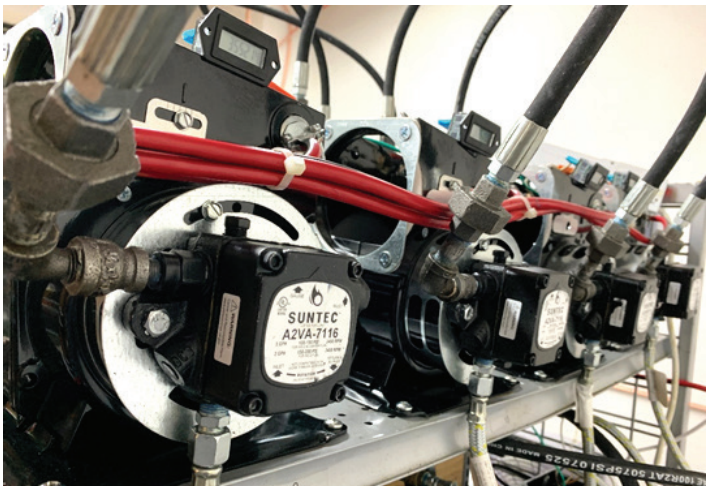
- Combustion performance
- Storage stability
- Impact on heating system metals
- Compatibility with burner system elastomers and seals
- Pump performance and durability
- Cold-weather behavior
- Filter performance

This work has not identified areas of significant concern in the use of biodiesel blends.

Underwriters Laboratories (UL), the organization that develops standard procedures for the safety approval of heating appliances, has made considerable progress in the modification of these procedures specifically for biodiesel blends up to B100 (100% biodiesel). As of the date of this report, fully approved burners for use with blends to B100 are available from all the residential oil burner manufacturers marketing in the U.S. Use of biodiesel blends up to 50% with No. 2 heating oil is now a common commercial practice. Field testing with biodiesel blends in heating oil at high levels, up to B100, continues (*Butcher 2023*).

To date, most of the renewable diesel consumption in the U.S. has been in transportation (truck engine) applications on the West Coast, driven by regional active clean fuel programs (U.S. EIA n.d.). In Europe, several important field tests involving the use of renewable diesel in heating systems have been completed with very positive results (FutureFuelReady n.d., Eurofuel n.d.).

Since 2018, NORA has conducted laboratory tests on RD as a standalone fuel and RD/BD blends in liquid fuel heating systems. Combustion performance curves for RD and RD/BD blends have been demonstrated to be closely comparable to those of No. 2 heating oil across a broad range of flue gas oxygen levels. Additional combustion compatibility was evaluated through transition testing, a NORA-developed method that compares two or more fuels under identical conditions. The fuels are switched without making any other changes to the burner, heating appliance or settings. Using this protocol, minimal changes in combustion parameters have been found among heating oil, RD, BD, and several blends of each of these fuels.



Component compatibility testing at the NORA Research Lab

Common elastomers used in fuel pumps and components, such as filters, were also confirmed to be compatible with these fuels. In cycling tests simulating 50 years of field operation, legacy pumps showed no greater wear with RD80/B20 than with conventional heating oil.

Long-term performance testing of RD50/B50 began in October 2025 using two commonly installed heating appliances and simulated more than

two years of field operation without intervention. This body of work has been shared at several conferences and meetings, within and outside the liquid fuels heating industry.



Monitoring RD and BD combustion at the NORA Research Laboratory

NORA's *Head Coking Project* has extensively studied carbon buildup on burner retention heads and end cones, commonly known as "head coking." This work has focused on understanding the causes of head coking and the methods by which it can be reduced. Short-term laboratory testing has identified several factors that influence this phenomenon. A deeper investigation into long-term effects of the most influential factors is underway. Findings to date indicate that combustion chamber design and burner cycling are the two strongest factors contributing to head coking. This field study provides an opportunity to assess the validity of these findings in real-world conditions. As such, detailed documentation of burner head conditions was recorded during site visits. Burner primary control data were used to obtain burner cycling patterns at these sites.

Based on this work, NORA and other industry stakeholders concluded that fuel blends of RD and BD were compatible with existing systems. NORA's Conversion of Oil-Fired Heating Systems to 100% Renewable Fuel field study was the next logical step. The results of this study are presented in this report. Blends of biodiesel and renewable diesel were evaluated in in situ heating systems across two states. While renewable diesel can be used alone as a drop-in fuel, the addition of biodiesel increases lubricity and can increase pump life. As of this writing, biodiesel is generally lower in cost than renewable diesel, enhancing market interest. The cold-flow properties of renewable diesel can be significantly better than those of biodiesel.

The goal of this project was to demonstrate that renewable diesel/biodiesel blends could serve as a fully renewable fuel in existing heating systems, with little or no conversion costs.

The following objectives were planned to achieve this goal:

- Work with liquid heating marketers/service organizations to identify test sites that represent the diversity of boilers, furnaces, and water heaters in the field
- Plan fuel supply and logistics to ensure participating liquid heating marketers would have the test fuels needed
- Evaluate changes in combustion performance after the conversion to the test fuels
- Plan and execute site visits to capture high-quality data on the performance over the course of the test
- Document service requirements and incidents over the course of the test
- Document opinions of liquid heating marketers, service technicians, and building owners about the test fuels

Methods

Site Selection

The field study aimed to obtain approximately 150 sites that would represent a wide range of conditions and heating system types in the field. Seven liquid heating marketers in Pennsylvania and three in Massachusetts agreed to participate and identify suitable locations. Each liquid heating marketer selected sites based on factors such as customer willingness, accessibility, and delivery efficiency. Sites with outside tanks were excluded as the effects of outside storage conditions on the test fuels were not within the scope of the project.

To support consistent data collection, the liquid heating marketers were charged with documenting details for each site, including site ID, appliance make and model, burner make and model, tank type and age and average annual fuel consumption. All site data collected from the liquid heating marketers were compiled into a single spreadsheet for further evaluation by the NORA research team.

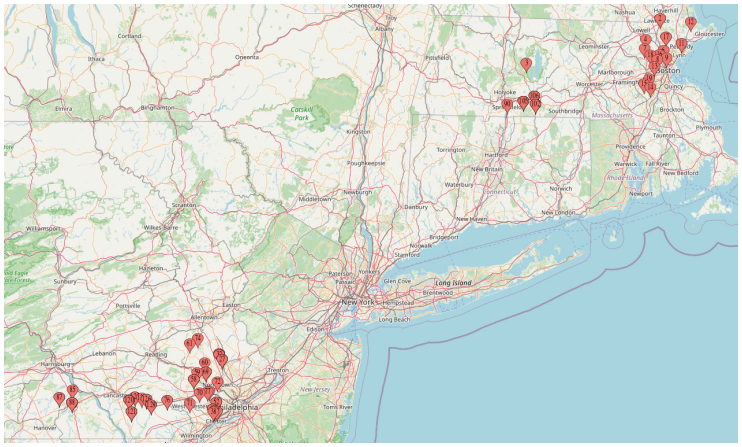
A total of 178 site entries were received from the liquid heating marketers. One liquid heating marketer in each participating state withdrew for logistical reasons, eliminating forty-eight sites. Several other sites were removed before or during the study because the storage tanks were outside, the site occupants moved, or a liquid heating marketer discontinued use of a facility building that was included in the study.

Finally, 121 sites were chosen to use a 100% renewable liquid fuel: either RD80/B20 or RD50/B50. Of these, eighty-four sites (69%) were located in Pennsylvania, and thirty-seven sites (31%) were located in Massachusetts. It must be noted that the seven standalone water heaters were considered as sites, but not as independent locations since they were collocated with a heating appliance. The final 121 sites were spread across 114 independent locations. The list of participating liquid heating marketers and their respective states is provided in Table 2. All site locations are shown on the map in Figure 1.

Table 2. Participating Liquid Heating Marketers

Distributor	State
Cubby Oil & Energy	MA
D.E. Duffey & Sons	PA
Moyer & Son Inc.	PA
Noonan Energy Corp.	MA
Oehlert Bros. Inc.	PA
Rhoads Energy	PA
Shipley Energy	PA
Wilson Oil & Propane	PA

Figure 1. Map showing all locations used in the study.



Appliances & Burners

The site appliances consisted of boilers, furnaces, and standalone water heaters representing twenty-eight different manufacturers. The distribution of appliance types is shown as a function of state and the total number of sites in Table 3.

Boilers account for most of the appliances in both states. They represent nearly identical

Table 3. Distribution of Test Sites

State	Boiler		Furnace		Water Heater	
	# of Sites	Percentage	# of Sites	Percentage	# of Sites	Percentage
MA	26	70	6	16	5	14
PA	58	69	24	29	2	2
Total	84	69	30	25	7	6

percentage of appliances in both states, similar to their distribution across all sites. Furnaces make up a larger proportion of sites in PA than they do in MA. This is consistent with anecdotal information on appliance usage within the two states. Water heaters, on the other hand, are represented to a greater degree in MA than in PA.

Burners manufactured by three companies are represented by the ninety sites for which the burner manufacturer is known. For the remaining thirty-one sites, the liquid heating marketers were unable to acquire that information. The distribution of burner manufacturers is shown as a function of state and the total number of sites in Table 4.

Table 4. Distribution of Burner Manufacturers

State	R.W. Beckett		Carlin Combustion		Riello	
	# of Sites	Percentage	# of Sites	Percentage	# of Sites	Percentage
MA	14	45.2	15	48.3	2	6.5
PA	55	93.2	2	3.4	2	3.4

R.W. Beckett Corp. burners are the most common across the study sites, followed by burners manufactured by Carlin Combustion Technology. However, the distribution varies by state. In Massachusetts, the two manufacturers account for nearly equal shares of the sites. In Pennsylvania, Beckett burners represent 93% of the study burners. Two Riello burners were used in each state.

Appliances and burners were not replaced for the study as the goal was to evaluate the fuels in existing heating systems. In a widespread transition to these fuels, most equipment would remain unchanged, making this a practical, real-world approach. There were, however, thirteen sites where old and/or faulty appliances (12 boilers, one furnace, each with a new burner) were replaced within three years prior to the study. Separate burner-only replacements were performed at two sites during the same period.

Fuel Storage & Usage

Annual fuel usage estimates were provided by the liquid heating marketers for eighty-six of the 114 independent sites. The estimate is typically calculated by using a combination of fuel delivered annually and the time between deliveries. Out of the eighty-six sites, the median fuel usage was 800 gallons. Twenty-five percent of the sites used 605 gallons or less, while 75% used 1,000 gallons or less. There are several outliers with high and low fuel consumption. For example, six sites used less than five hundred gallons of fuel annually, likely due to the use of secondary heating appliances such as wood stoves. On the other hand, eleven locations were high-consumption sites with annual usage between 1,300 and 2,500 gallons. These sites consist of large homes, office buildings, and college dormitory buildings. Based on this fuel consumption data, the research team concluded that site utilization of heating systems adequately represented fuel utilization of the liquid fuels market overall.

The age range of the fuel storage tanks was provided by the liquid heating marketers for sixty-seven of the 114 locations. Liquid heating marketers were asked to select one of three age groups: 1-5 years, 6-20 years, and greater than 20 years. The distribution of the sites across these groups is shown in Table 5. Tank ages were unknown at the remaining locations because the respective marketers had not installed the tanks, delivered fuel but did not provide contracted service, or otherwise could not determine the tanks' ages.

Table 5. Age Distribution of Fuel Tanks

Age Range (years)	# of Sites
1-5	12
6-20	33
over 20	22

Given the age of many fuel storage tanks, several were expected to contain water, degraded fuel, bacterial growth, or other contaminants that could reduce fuel quality. Despite this, the tanks were not cleaned, emptied, or replaced at any of the sites in preparation for the test as it is unlikely that such a measure would be taken in the case of widespread adoption of this new fuel. At one site, the research team recommended a tank replacement because of high amounts of biological growth found during the pre-test fuel analysis. More information on this site is provided in the results section. During the test, an approximately 50-year-old tank was replaced by the homeowner as a precaution. There were also seven sites where the fuel tanks were replaced within three years prior to the beginning of the study.

Service & Delivery Data

Site service data are vital to this study. In this study, "service" is defined as any time a heating technician visits a site for any reason, including a "no-heat call" or general troubleshooting. Yearly maintenance visits or "tune-ups" were not considered service calls and were excluded from the analysis unless an issue outside the parameters of a tune-up was uncovered during one of the visits. At the request of the research team, the liquid heating marketers provided service data for all sites dating back three years prior to the beginning of the study. They also provided ongoing service data for the duration of the study. The information in each instance of a service call included the reason for the visit, any changes made to the system, and whether the issue was resolved.



NORA's Combustion Lab monitoring appliance performance

Past service data were used to identify sites with recurring issues. They were also used for comparison with ongoing service data to characterize any operational changes in the systems that may have been caused by the test fuel. If a service call during the test period was suspected to be fuel related, the research team interviewed the attending technicians to make a conclusive determination. In some cases, the team also performed further analysis of related defective parts at no cost to the liquid heating marketer.

All fuel for this testing was supplied by Chevron and sold to the liquid heating marketers at price parity with heating oil. The liquid heating marketers were responsible for handling delivery logistics to their respective sites. In all cases, the liquid heating marketer reserved a truck to exclusively manage and deliver the test fuels to avoid mixing with non-test fuels. These trucks were refilled from one of three regional locations.

- Northeast Massachusetts – separate shipments of RD and BD
- South Central Pennsylvania – RD80/B20
- Southeast Pennsylvania – RD80/B20

The Massachusetts location received separate shipments of RD and BD because each liquid heating marketer used a different blend of the two fuels. Using the blending capabilities of the storage facility, each marketer received the respective fuel they needed.

For the test, Chevron delivered approximately 50,000 gallons of RD by rail from its refinery in Geismar, Louisiana. Chevron also delivered about 50,000 gallons of biodiesel by rail from Danville, Illinois. These were blended at the Broco Energy facility in Massachusetts at either RD80/B20 or RD50/B50 blend levels. The fuel for all the Pennsylvania sites was preblended at RD80/B20 in Louisiana and shipped by rail to a transload facility in Strasburg, PA. From here it was picked up by trucks from Oehlert Bros. Inc. and Rhoads Energy Corporation, and brought to their storage facilities. All the other marketers in Pennsylvania picked up fuel from the loading rack at Oehlert or Rhoads. Chevron delivered about 175,000 gallons of the test blend to Strasburg.

The research team obtained fuel delivery data from each of the liquid heating marketers over the course of the test period. In some cases, the data were provided after each delivery day, while in other cases bulk delivery data were provided periodically. These data were used to estimate when each site fully transitioned to the test fuel.

Site Level Designations

Visiting all the test sites for detailed inspections and fuel sampling on a periodic basis was not seen as feasible. Therefore, a select number of sites were chosen for detailed field monitoring in conjunction with service data tracking. These sites were designated as Level 1. The remaining sites were designated as Level 2 and would be analyzed using service data.

The research team provided the liquid heating marketers with the option to select Level 1 sites. Four of the eight obliged by selecting 13 Level 1 sites. These sites all used boilers and did not include furnaces or water heaters. Findings from the *Head Coking Project* indicated cold chamber boilers, typically known as triple pass boilers, needed to be included as well.

It was important to capture the performance of the fuel in furnaces and water heaters to ensure this study reflected the wide diversity of heating appliance types in this market. This, along with additional building owners' willingness to participate in site visits, allowed for the addition of 15 more Level 1 sites. Some of these were added after the pre-test visits were performed.

Further consideration was given to ensure that the three most common burner manufacturers were adequately represented.

Table 6 contains descriptions of each of the Level 1 sites. For reference, single-pass or pin-type boilers with refractory-lined combustion chambers are classified as 'hot chamber' boilers, while triple pass boilers are classified as 'cold chamber' boilers. Furnaces and water heaters are considered 'hot chamber' appliances.

Out of the 28 Level 1 sites, 11 (39%) were in MA and the remaining 17 (61%) were in PA. The sites were mostly homes, with two office buildings and two college buildings included in the list. The appliance category was made up of boilers, furnaces, and water heaters, manufactured by fourteen companies. Representation of the three primary residential burner manufacturers was found to be satisfactory.

The research team performed five planned data and fuel collection visits to each of the Level 1 sites between October 2024 and May 2026. The time period of each visit is outlined in Table 7.

During the Visit 5 period (Spring 2026), nineteen Level 2 sites were also visited. All visits were made by at least one member of the NORA team accompanied by personnel representing the liquid heating marketers (e.g., service technician, service manager, owner, etc.).

A thorough inspection of the system was conducted during every visit to ensure that there were no performance issues. Data on burner operating parameters, including O_2, CO_2, CO concen-

Table 6. Level 1 Test Sites

Site ID	Type	Town	State	Unit Type	Burner	Fuel Blend
1	Home	North Andover	MA	Cold chamber boiler	Carlin	RD50/B50
2	Home	North Andover	MA	Cold chamber boiler	Beckett	RD50/B50
3	Home	Billerica	MA	Hot chamber boiler	Carlin	RD50/B50
4	Home	Bedford	MA	Cold chamber boiler	Beckett	RD50/B50
5	Home	Malden	MA	Hot chamber boiler	Carlin	RD50/B50
6	Home	North Reading	MA	Cold chamber boiler	Carlin	RD50/B50
7	Office	Souderton	PA	Hot chamber boiler	Beckett	RD80/B20
8	Other	Souderton	PA	Furnace	Beckett	RD80/B20
9	Home	Hatfield	PA	Hot chamber boiler	Beckett	RD80/B20
10	Home	Media	PA	Hot chamber boiler	Beckett	RD80/B20
11	Home	Swarthmore	PA	Furnace	Riello	RD80/B20
12	Home	Media	PA	Furnace	Riello	RD80/B20
13	Home	Broomall	PA	Furnace	Beckett	RD80/B20
14	Home	Broomall	PA	Water heater	Beckett	RD80/B20
15	College	Collegeville	PA	Hot chamber boiler	Carlin	RD80/B20
16	College	Collegeville	PA	Furnace	Beckett	RD80/B20
17	Home	Malvern	PA	Hot chamber boiler	Carlin	RD80/B20
18	Home	Norristown	PA	Hot chamber boiler	Beckett	RD80/B20
19	Home	York	PA	Furnace	Beckett	RD80/B20
20	Home	Dover	PA	Cold chamber boiler	Beckett	RD80/B20
21	Office	Springfield	MA	Cold chamber boiler	Carlin	RD80/B20
22	Home	Wilbraham	MA	Cold chamber boiler	Riello	RD80/B20
23	Home	Wilbraham	MA	Cold chamber boiler	Carlin	RD80/B20
24	Home	Wilbraham	MA	Furnace	Beckett	RD80/B20
25	Home	Wilbraham	MA	Water heater	Carlin	RD80/B20
26	Home	Quarryville	PA	Hot chamber boiler	Beckett	RD80/B20
27	Home	Quarryville	PA	Hot chamber boiler	Beckett	RD80/B20
28	Home	Kinzers	PA	Furnace	Beckett	RD80/B20

tration, efficiency, cad cell resistance, and cycle count were collected. The severity of carbon deposits, more commonly known as head coking, was documented by taking pictures of the retention head, end cone, and burner air tube. For burners with removable retention heads, the nozzle assembly was removed so the burner head could be photographed. Burners with fixed retention heads were removed from the boiler for photography.

Table 7. Level 1 Site Visit Periods

Visit #	Date Range
1	October-November 2024 (pre-delivery of test fuels)
2	March-April 2025
3	September-October 2025
4	January 2026
5	May 2026

While the goal was to allow the test fuel to be used in the heating systems under the same conditions as conventional heating oil, some planned changes were made. These included changing the burner primary controls at four sites during Visit 2 (Spring 2025) to allow easier access to burner operation data such as cad cell resistance, cycle counts, fault history, etc. Additionally, the retention head was replaced at six sites at various points during the 2025/26 heating season. This allowed for analysis of head coking progression from a known starting point.

Fuel samples were collected to evaluate the quality and stability of renewable diesel (RD) and biodiesel (BD) blends. Samples were obtained directly from the storage tank at each site. A sample representing the bulk fuel was collected from approximately halfway up the tank. A second sample was collected from the bottom of the tank to monitor the presence of contaminants such as sludge and water. Pump bleeder fuel samples, combustion readings, and head photos along with system type and basic operational details were collected. All fuel samples underwent rigorous testing in the NORA Fuel Chemistry Laboratory.

Analysis of Fuel Samples

Samples were collected in pre-cleaned, quart-sized metal cans with airtight lids to limit light exposure and oxidation. Each sample was labeled with date, location, and fuel sampling location (middle or bottom). Samples were transported to the laboratory under controlled conditions. Testing was initiated within recommended holding times to prevent compositional changes.

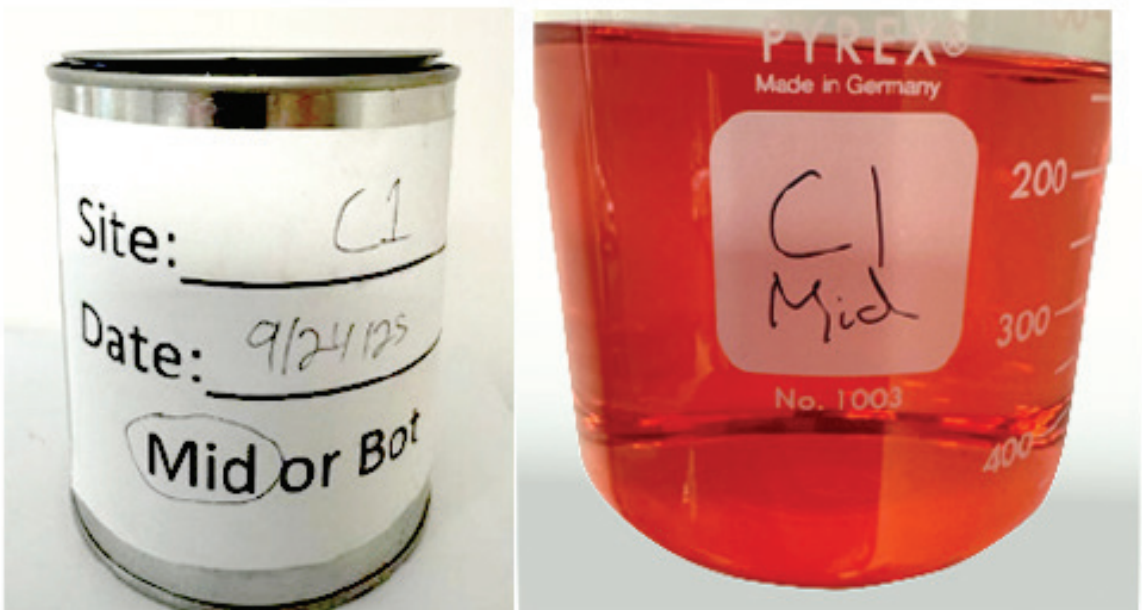
At the NORA Fuel Chemistry Lab in Plainview, NY, tests were run on each sample to determine the quality of the fuel and to measure any changes to the fuel over the test period. This testing included:

- Biodiesel content (middle fuel sample)
- Oxidative reserve (middle fuel sample)
- Acid number (middle fuel sample)
- Water content (bottom fuel sample)
- Biological content (bottom fuel sample)
- Density (middle fuel sample)
- Viscosity (middle fuel sample)
- Water and sediment (bottom fuel sample)

In total, approximately 280 fuel samples were collected from the Level 1 site locations. Examples of the containers used to store the fuels and a middle tank sample are seen in Figure 2.

The percentage of biodiesel in the RD/BD blends was used to monitor that the correct fuel blend was delivered to each location. At each visit, the fuel taken from the middle of the tank was tested. The biodiesel content was determined using Fourier Transform Infrared Spectroscopy (FTIR) in accordance with ASTM D7371. The method quantifies fatty acid methyl ester (FAME) concentration based on characteristic ester absorption bands. A Thermo Scientific Nicolet iS20 FTIR was used to make biodiesel content measurements.

Figure 2. Example of fuel collection container (left) and a middle tank fuel sample (right)



Calibration standards covering the expected biodiesel concentration range were prepared using certified reference materials. Each sample was analyzed, and results were reported as volume percent biodiesel (% v/v).

Oxidative stability testing was performed to evaluate the resistance of the fuel blends to chemical degradation during storage and use. Reduced oxidative stability indicates increased susceptibility to formation of peroxides, organic acids, gums, and insoluble degradation products, all of which can negatively impact fuel quality.

Oxidative stability was evaluated using an accelerated oxidation procedure consistent with EN 15751 using a Metrohm 893 Professional Biodiesel Rancimat. Fuel samples were exposed to an elevated temperature (110°C) under continuous airflow (10 L/h), promoting the formation of volatile organic acids. These organic acids are transferred by the airflow into a vessel containing deionized water. A conductivity probe monitors changes in the water over time, with a rapid change in conductivity marking the induction point. Oxidative reserve was reported as induction time (h), representing resistance to oxidative degradation during storage. ASTM D396 B20 specification calls for an oxidative reserve of a minimum of six hours. At each visit, the fuel taken from the middle of the tank was tested.

Total Acid Number (TAN) is a measurement of acidity in oils and lubricants. It is defined as the number of milligrams of potassium hydroxide (KOH) needed to neutralize all acidic compounds in one gram of a sample. It is used to monitor fuel degradation. The Total Acid Number was determined using potentiometric titration according to ASTM D664. Samples were dissolved in a mixture of toluene and propan-2-ol and titrated with standardized potassium hydroxide solution to a determined endpoint. A manual titration was performed with the electrode potential measured with an Oakton pH 700 Benchtop Meter. Results were expressed as milligrams of potassium hydroxide per gram of fuel (mg KOH/g). ASTM D396 B20 specification calls for a maximum acid number of 0.3 mg KOH/g.



Determining biodiesel content at the NORA Fuel Chemistry Lab

Bound water content was measured to quantify dissolved and emulsified water retained within the fuel samples. Elevated dissolved water levels can accelerate oxidation reactions, promote microbial growth, and contribute to long-term storage instability. Water content was measured using coulometric Karl Fischer titration following ASTM D6304. Samples were introduced directly into the titration cell under controlled conditions to prevent atmospheric moisture interference. The method quantifies dissolved and emulsified water present within the fuel matrix. A Metrohm 917 Coulometer was used to make these measurements. Water concentrations were reported in parts per million (ppm).

At each visit, the fuel taken from the bottom of the tank was tested. Water and sediment testing was performed to evaluate the presence of free water and particulate contamination within the fuel systems. Free water accumulation can promote corrosion, microbial proliferation, and fuel degradation, while sediment may contribute to filter plugging and operational issues in heating systems. Free water and sediment were determined using the centrifuge method described in ASTM D2709. Water and sediment should not exceed 0.05% v/v according to ASTM D396. Samples were centrifuged under standardized conditions to separate immiscible water and particulate material from the fuel phase. The separated volume was measured directly using calibrated centrifuge tubes. Results were reported as percent volume (% v/v) of combined water and sediment.

Testing for water and sediment from the bottom of the tank was performed during Visits 1, 3, 4, and 5. It was decided not to test this parameter at Visit 2, to allow the tanks more time to adjust to the newly introduced fuels.

Microbial contamination was evaluated using cellular adenosine triphosphate (cATP) measurements to estimate viable bacterial biomass present within the fuel systems. ATP is present in metabolically active cells and serves as a rapid indicator of biological activity. Elevated cATP levels indicate active microbial contamination, which may contribute to fuel degradation, acid formation, sludge accumulation, corrosion, and operational problems within storage and heating systems. These measurements were made using a LuminUltra rapid microbial detection system. At each visit, the fuel taken from the bottom of the tank was tested. Microbial content was measured for all samples at Visits 1 and 5. During Visits 3 and 4, if water was detected in the fuel in the water and sediment testing, then microbial contamination was measured as well.

Each fuel sample was processed using manufacturer-recommended extraction reagents designed to release microbial ATP into an aqueous phase. Following extraction, samples were combined with a luminase reagent, and emitted light was measured using a portable luminometer. Measured bioluminescence is proportional to ATP concentration and provides a rapid estimate of biological activity within the fuel. LuminUltra recommends that fuel values (pg cATP/mL) remain below 100 and that corrective action be taken when values exceed 1,000.

Density measurements were conducted to evaluate changes in fuel composition and bulk physical properties of the fuel blends. Fuel density can influence volumetric energy content, fuel injection characteristics, and combustion performance in heating appliances. Variations in density can also be used as a secondary method for confirming the fuel blend ratio. According to ASTM D396, density at 15 °C should be a maximum of 0.876 g/cm³.

Fuel density was determined at 15 °C using an Anton Paar SVM 3001 density meter in accordance with ASTM D4052. Prior to analysis, the instrument was calibrated using air and certified density reference standards. Samples were equilibrated to the measurement temperature before analysis to minimize thermal effects. Density values were reported in grams per cubic centimeter (g/cm³).

Kinematic viscosity was measured to assess the flow behavior and atomization characteristics of the fuel blends. Viscosity directly affects burner performance, spray formation, fuel delivery, and combustion efficiency in residential heating systems. Kinematic viscosity was measured at 40 °C following ASTM D445 using an Anton Paar SVM 3001 kinematic viscometer. According to ASTM D396, kinematic viscosity should be between 1.9 and 4.1 mm^2/s. Samples were temperature-equilibrated in a constant-temperature bath prior to measurement to ensure thermal stability. Efflux times were recorded and converted to kinematic viscosity using viscometer calibration constants. Results were reported in square millimeters per second (mm^2/s). Both the density and kinematic viscosity testing were conducted by Chevron Corporation on the middle fuel samples.

Results

Service Data

Service records covering November 2021 through May 2026, including the three years before the study began, were obtained for 109 of the 121 sites. No data were available for the remaining twelve sites. Of these, seven sites at a college were maintained by in-house facilities staff who did not provide service data, four sites were homes that received fuel but no service from their liquid heating marketers and the final one did not have service records. An additional twenty sites from one liquid heating marketer were excluded because the data did not contain important information, such as technician diagnoses of issues and subsequent corrective measures. As a result of the omissions, the analysis of this section includes data for eighty-nine sites from seven different liquid heating marketers.

Service calls were divided into the following two categories:

- **General:** This includes issues not caused by the fuel. Examples include issues involving hydronic-system, ductwork, and electrical components.
- **Fuel/Fuel System Related:** These include fuel pump, nozzle, filter, and flame-sensing failures. Boiler and chimney blockages or failures due to poor combustion are also included in this category. However, no such instances occurred.

Service calls were further grouped by whether they occurred before or during the study. Fuel delivery data to the sites were used to ensure that this distinction was made correctly. For example, a pump failure at Site 74 occurred during the study period, but the site had not yet received any test fuel deliveries. Therefore, this service call was categorized as "Before Study."

In the three-year period prior to the study, 80 service calls were recorded; 22.5% were determined to be fuel/fuel system related. In contrast, 56 service calls were recorded during the study, of which 26.8% were fuel/fuel system related. Applying this normalization approach on a site-by-site basis shows an increase in the rate of fuel/fuel system related service calls for thirteen sites and a decrease at ten sites during the study period. The remaining sixty-six sites did not experience any change.

The change in yearly rate of fuel/fuel system related service calls varied among the liquid heating marketers. Three out of seven experienced a decrease in the yearly rate of fuel/fuel system related service calls, while three saw an increase. One liquid heating marketer's yearly rate remained the same. fuel/fuel system relatedservice calls occurred on fifteen separate occasions.

Fuel-pump failures caused four service calls: two at Site 8 (Level 1), one at Site 9 (Level 1), and one at Site 80 (Level 2). The service technician replaced only the fuel pump in all four cases.

The two pump failures at Site 8 occurred on 4/16/2025 and 12/4/2025. The first failed pump was disassembled for examination by the research team. Particulate deposits were observed on the gearset of the pump. Fuel at this site is supplied using a two-pipe system where fuel is drawn by the pump at approximately 20 times the rate of consumption and the excess fuel flows back to the tank. It must be noted that the system at this site had not been serviced since its installation in 2018 until March 2025. The fuel particulate concentration at this site was measured and found to be 62 mg/L, which is above the typically accepted value of 20 mg/L. This test was done in addition to Level 1 fuel quality testing.

Site 80 also has a two-pipe fuel supply system. Although it is not a Level 1 site, a fuel sample was collected from the tank for further analysis. The filterable particulate concentration at this site was found to be very high.

The pump failure at Site 9 occurred on 3/6/2026. Fuel was delivered to this site on the same date. The fuel tank was replaced on 12/4/2025 as a precaution since it was more than 50 years

old. Additionally, heavy sludge buildup was observed in that tank during Level 1 fuel collection. Only typical Level 1 fuel quality testing was performed on the fuel from this site. Those test results can be found below in the section on Fuel Analysis.

There were four service calls due to failed nozzles, occurring twice at Site 22 and once each at Sites 44 and 46. Site 44 received a fuel delivery nine days prior to the service call on 12/18/2025. Site 46 did not receive a fuel delivery within a month prior to the failed nozzle on 12/7/2025. Specific delivery dates for Site 22 are not known.

Blocked filters caused two service calls, once each at Sites 19 and 88. In both cases, the filter element and nozzle were replaced. At Site 88, a fuel delivery was made ten days prior to the service call. No deliveries were made within a month of the service call at Site 19.

Burner primary controls detect the presence of a flame by the response from a cadmium sulfide photoconductor (commonly referred to as a cad cell) which has near-infinite resistance in darkness and low resistance in the presence of visible light. All controls that read cad cell data use a preset threshold resistance value below which the presence of a flame is confirmed. Under some conditions, including higher excess air settings and colder chambers, older controls (nominally 20 years or older) may not sense the presence of the flame and may stop burner operation. Control manufacturers have been introducing newer controls to the market that respond better to less luminous flames. Burner shutdowns occurred at four sites using older controls (Sites 93, 95, 102, and 104). In all cases, the control was simply upgraded to a newer model. The issue did not recur at any of the sites.

Carbon buildup on the nozzle caused improper atomization at Site 120. This was resolved by replacing the nozzle and cleaning the nozzle assembly.

Flue gas O_2 and CO_2 remained within burner manufacturers' recommended specifications throughout the study period for most sites. Some sites were set up by technicians to O_2 levels higher than recommended because they felt the ambient environment conditions had the potential to block airflow over time (e.g., shop environment with dust and particulates, pet areas in the vicinity of the burner). The research team did not adjust burner air settings in those cases. At some sites, there were small variations in O_2 readings between visits. These could be attributed to natural changes in combustion due to varying draft or lint buildup in the fan assembly.

On a few occasions, the excess air was also adjusted by an attending technician while performing an annual maintenance or a service call which also resulted in varying O_2 readings between visits. Flue gas CO was found to be very low (<10 ppm) to below measurement limits in all cases, except for one occasion each for Sites 10, 22, 45 and 59. For Sites 10, 22 and 59, corrective measures were taken to reduce CO levels below 10 ppm. At Site 45, the CO reading was 35 ppm and all other measurements within specifications, therefore, no corrective measures were needed. Air adjustments were performed to lower flue gas O_2 at three sites to make the flame less lean and ensure that flame luminosity was sufficient for the older controls being used.

Analysis of Collected Fuel Samples

Biodiesel Content

As displayed in Table 8, biodiesel concentrations showed considerable variability across sampling locations before the introduction of the RD/BD blend fuel. Initial measurements (Visit 1) showed a wide distribution ranging from 0 to 100% v/v, with many of the sites located in Pennsylvania starting with 0% biodiesel. At the other end of the spectrum, Sites 1 through 4 started the test with nearly 100% biodiesel in their fuel storage tanks.

Table 8. Biodiesel Content Measured at Each Site Across the Five Site Visits

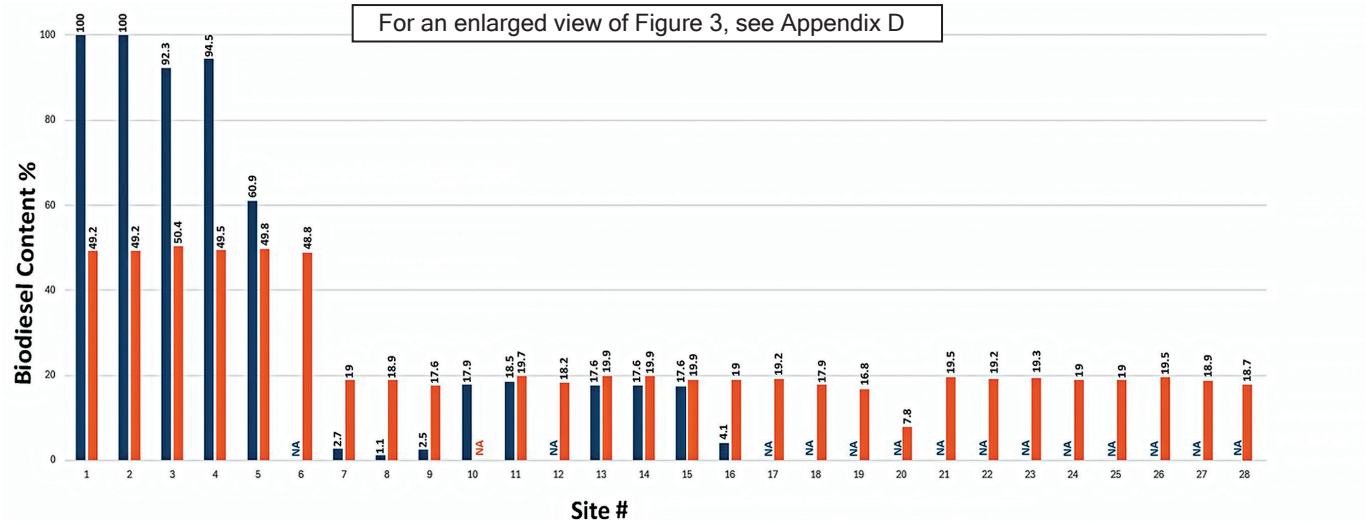
Site Number	Visit 1 (%)	Visit 2 (%)	Visit 3 (%)	Visit 4 (%)	Visit 5 (%)
1	100.0	49.2	49.7	50.9	49.6
2	100.0	49.2	49.7	50.9	49.6
3	92.3	50.4	49.0	48.6	40.1
4	94.5	49.5	48.3	49.8	39.2
5	60.9	49.8	38.9	45.2	48.7
6	-	48.8	47.5	49.2	48.8
7	2.7	19.0	18.8	12.0	23.1
8	1.1	18.9	18.3	19.1	15.4
9	2.5	17.6	17.1	9.9	22.6
10	17.9	-	19.8	19.2	24.6
11	18.5	19.7	19.9	19.2	22.0
12	-	18.2	-	19.0	22.2
13	17.6	19.9	19.6	19.3	23.8
14	17.6	19.9	19.6	19.3	23.8
15	17.4	19.0	19.3	12.8	19.9
16	4.1	19.0	19.0	12.0	17.9
17	0.0	19.2	18.8	5.1	6.3
18	0.0	17.9	18.8	13.8	11.3
19	-	16.8	16.8	18.7	23.9
20	0.0	7.8	8.3	14.6	14.6
21	-	19.5	19.2	19.6	19.1
22	-	19.2	19.9	19.4	2.9
23	-	19.3	19.4	19.4	18.5
24	0.0	19.0	19.3	19.5	19.3
25	0.0	19.0	19.3	19.5	19.3
26	0.0	19.5	8.5	21.5	24.5
27	-	18.7	19.9	10.7	13.6
28	0.0	-	-	29.8	25.1

After the delivery of the test fuel between Visits 1 and 2, the biodiesel content of most sites began to reach the desired levels (B50 for Sites 1–6, B20 for Sites 7–28). This can be observed in Figure 3. As more fuel deliveries were made throughout the test period, subsequent sampling (Visits 2–5) demonstrated more consistent biodiesel concentrations. Average values remained relatively stable (23.8–25.5% v/v), while variability decreased significantly compared to Visit 1. The B50 and B20 clusters remained fairly concentrated through all following site visits.

Outliers observed in Visits 2–5 were limited but still present. Site 20 showed a gradual increase in biodiesel content with the biodiesel level increasing at a much slower rate than all other sites. Visit 4 also saw a decrease in biodiesel content at a select number of sites (Sites 7, 9, 15–18). The most likely cause of this was the delivery of the incorrect blend level to the sites. This issue was still present in Visit 5, with some sites having slightly lower or higher biodiesel concentrations

than expected. Most locations did move towards the desired B20 or B50 level. The average biodiesel concentrations went from 23.8% on Visit 4 up to 24.6% on Visit 5.

Figure 3. Biodiesel content change between Visits 1 and 2, showing the sites reaching the desired biodiesel levels.



Oxidative Stability

Oxidative stability, as measured by Rancimat induction time, varied across sites and visits. Mean induction times ranged from 6.8 to 13.7 hours across the five sampling events. Because many of the test sites in Visit 1 contained fuels with no level of biodiesel, the Rancimat test could not provide accurate results for these samples. This led to Visit 1 having far fewer oxidative reserve results than the subsequent visits.

Samples collected during Visit 2 exhibited the highest average stability (13.7 h), with a relatively broad distribution and a maximum value of 26.8 h, indicating the presence of highly stable fuel blends. In contrast, Visit 3, which was made after a summer shutdown period at the start of heating season, showed the lowest mean induction time (6.8 h) and a higher number of samples near or below the ASTM threshold. Visit 4 showed intermediate performance with a mean of 8.7 h, but with the continued presence of low-stability samples, as indicated by a minimum induction time of 2.5 h. The average stability continued to rise into Visit 5 (9.8 hrs) as heating season continued. As seen in Table 9, by the end of heating season in Visit 5, 82% of the samples had an oxidative reserve over 6 hrs, compared to Visit 3 at the beginning of heating season when only 65% of samples met this threshold.

Table 9. Number of Samples with Oxidative Reserve at Least 6 Hours

Visit	# of samples with Oxidative Reserve ≥ 6 hrs	Total Sample Count	Number of Samples in Range (%)
1	11	14	79
2	22	25	88
3	17	26	65
4	17	28	61
5	23	28	82

As can be seen in the statistical data provided in Table 10, compliance with ASTM D396 varied across visits. The majority of samples measured for all visits met or exceeded the 6-hour requirement, indicating generally acceptable oxidative stability. Of the fuel samples below the 6-hour limit, Visit 3 had some sites with oxidative reserves less than 1 hour (Sites 6, 9, and 15). While Vis-

it 4 had the same number of sites below the ASTM threshold, the overall stability was on an upward trajectory. Many, but not all, of the site locations that experienced low stability at Visit 3 showed a direct improvement by Visit 4. Site 6, for example, increased from an oxidative reserve of <1 hour in Visit 3 to an oxidative reserve of 17 hours in Visit 4. Fuel deliveries were made to this site during this time, allowing the introduction of new fuel to the system.

Table 10. Average, Standard Deviation, Minimum and Maximum Values Measured for Oxidative Reserve at Each Visit

	Visit 1 (hrs)	Visit 2 (hrs)	Visit 3 (hrs)	Visit 4 (hrs)	Visit 5 (hrs)
Average	9.7	13.7	6.8	8.7	9.8
Standard Deviation	4.7	7.0	4.0	5.1	5.1
Minimum	2.5	0.6	0.6	2.5	2.2
Maximum	19.3	26.8	15.6	19.7	22.4

Total Acid Number (TAN)

Total Acid Number measurements show generally low acidity across the test period. In most cases, the TAN measurements were below the ASTM D396 limit of 0.3 mg KOH/g. Mean TAN values ranged from 0.15 to 0.27 mg KOH/g across the five sampling events. A subset of sites showed TAN values exceeding the recommended threshold, with maximum values reaching 0.96 mg KOH/g from Visit 2 and 1.30 mg KOH/g from Visit 3.

Compliance with the 0.3 mg KOH/g limit varied by visit. As shown in Table 11, Visit 1 (81%) and Visit 3 (81%) exhibited the lowest compliance rates below the threshold. Visit 2 demonstrated higher compliance (92%), followed by Visit 4 (96%), indicating improved fuel quality and consistency during these periods. In contrast, Table 11 shows that by the final collection and the end of heating season, the fuel collected in Visit 5 had 100% of the samples below the 0.3 mg KOH/g limit.

Table 11. Number of Samples with TAN less than or equal to 0.3 mg KOH/g

Visit	# of samples with TAN ≤ 0.3 mg KOH/g	Total Sample Count	Number of Samples in Range (%)
1	17	21	81
2	23	25	92
3	21	26	81
4	27	28	96
5	28	28	100

In the case of Visit 1, this could reflect the varied conditions of the fuel present at the start of the test. Visit 3 showed the highest mean TAN (0.27 mg KOH/g), which could be due to the months-long period before Visit 3 in which no fuel was delivered to most sites. The presence of outliers exceeding 1.0 mg KOH/g further supports the occurrence of degradation in a subgroup of samples. Although Visit 1 exhibited several elevated values, overall acidity remained lower than in Visit 3.

Table 12. Average, Standard Deviation, Minimum and Maximum Values Measured for TAN at Each Visit

	Visit 1 (mg KOH/g)	Visit 2 (mg KOH/g)	Visit 3 (mg KOH/g)	Visit 4 (mg KOH/g)	Visit 5 (mg KOH/g)
Average	0.16	0.22	0.27	0.16	0.15
Standard Deviation	0.16	0.16	0.22	0.05	0.05
Minimum	0.03	0.12	0.12	0.09	0.06
Maximum	0.68	0.96	1.30	0.31	0.27

In contrast, Visits 4 and 5 demonstrated both the lowest variability

and near-complete compliance with the specification, with only a single sample exceeding the 0.3 mg KOH/g threshold. For both visits, the standard deviation of the data is also much lower, further demonstrating close compliance with the ASTM limit. This improvement may reflect stabilization of the fuel supply and reduced residence time in storage during the heating season.

Overall, testing demonstrated that the majority of samples did not exceed the 0.3 mg KOH/g limit set by ASTM D396. Most sites demonstrated no excess acidity during any collection period. In the case of the sites that did experience elevated acid numbers, the elevated acid numbers may be linked to site-specific conditions.

Bound Water Content

Bound water content exhibited considerable variability across sampling locations and visits, reflecting the unique environment that can develop in a storage tank. Measured water concentrations ranged from 9 to 1781 ppm, with sizable differences observed among sampling events.

Table 13 shows the mean water content increased from 96 ppm in Visit 1 to 116 ppm in Visit 2, followed by a marked increase to 235 ppm in Visit 3. This elevated mean in Visit 3 was accompanied by a large standard deviation (317 ppm), driven by the presence of a significant outlier (1781 ppm). There are a number of factors that could have led to the elevated level measured in Visit 3, including increased temperature and humidity in the summer period or the lower fuel usage associated with being outside of the heating season.

Table 13. Average, Standard Deviation, Minimum and Maximum Bound Water Content Measured on Each Visit

	Visit 1 (ppm)	Visit 2 (ppm)	Visit 3 (ppm)	Visit 4 (ppm)	Visit 5 (ppm)
Average	96	116	236	98	237
Standard Deviation	75	63	323	98	212
Minimum	15	9	65	23	55
Maximum	244	285	1781	438	878

Visit 4 demonstrated a decrease in average water content to 103 ppm relative to Visit 3, indicating partial recovery with the move into an active heating season. However, variability remained evident, as observed by the standard deviation (97 ppm) being higher than the values observed in Visit 1 and 2 and with values extending up to 438 ppm. Visit 5 again showed an increase in average water content to 237 ppm.

While most sites had low measured water content, a few sites had elevated levels for most of the testing period. Site 5 had the highest water content at multiple points throughout the study with the measured values at this site being 135 ppm, 285 ppm, 1,781 ppm, 438 ppm, and 451 ppm, respectively. The elevated water content observed in Visit 3 was particularly significant, as water can promote microbial growth, accelerate oxidative degradation, and contribute to corrosion and operational issues in fuel systems. The presence of high outliers suggests that water contamination may be specific to particular locations rather than uniform across all study sites.

Water and Sediment

Water and sediment levels were consistently elevated across all visits, with many samples exceeding the ASTM D396 specification limit of 0.05% by volume. This is to be expected when evaluating tank bottom samples. Measured values ranged from below detection limits (<0.005%) to greater than 0.5% v/v, with a large proportion of samples clustered at or above 0.2% v/v. Tables 14, 15, and 16 provide data on the presence of water and sediment in the fuel samples. At the

Table 14. Water and Sediment at Each Site Over Four Site Visits

Site Number	Visit 1 (% by volume)	Visit 3 (% by volume)	Visit 4 (% by volume)	Visit 5 (% by volume)
1	<0.005	0.005	0.01	>0.5
2	<0.005	0.005	0.01	>0.5
3	0.5	0.2	0.1	0.2 (water)
4	0.3	0.05	0.01	0.5
5	>0.5	>0.5 (water)	>0.5 (water)	>0.5 (water)
6	-	0.01	0.01	0.3 (water)
7	>0.5	>0.5 (water)	>0.5	0.01
8	>0.5	0.01	>0.5	0.5 (water)
9	>0.5	>0.5 (water)	0.05	0.05
10	>0.5 (water)	0.4 (water)	>0.5 (water)	>0.5 (water)
11	>0.5 (water)	>0.5 (water)	>0.5 (water)	>0.5 (water)
13	>0.5 (water)	0.4 (water)	0.4 (water)	0.1 (water)
14	>0.5 (water)	0.4 (water)	0.4 (water)	0.1 (water)
15	>0.5	0.3	0.05	0.05
16	0.4	0.05	>0.5	0.05
17	0.01	0.01	0.01	0.01
18	>0.5 (water)	0.05 (water)	0.01 (water)	0.005
19	-	>0.5 (water)	>0.5 (water)	0.5 (water)
20	>0.5 (water)	0.05	0.2 (water)	0.01
21	-	0.2	0.01	0.01
22	-	0.5 (water)	0.2	0.01
23	-	0.02	0.02	0.2
24	>0.5	>0.5	0.4 (water)	>0.5
25	>0.5	>0.5	0.4 (water)	>0.5
26	0.2	0.01	0.05	0.05
27	-	0.4	0.2	0.01
28	0.1	-	0.05	0.02

Table 15. Presence of Water

Site #	Visit 1	Visit 3	Visit 4	Visit 5
1	No	No	No	No
2	No	No	No	No
3	No	No	No	Yes
4	No	No	No	No
5	No	Yes	Yes	Yes
6		No	No	Yes
7	No	Yes	No	No
8	No	No	No	Yes
9	No	Yes	No	No
10	Yes	Yes	Yes	Yes
11	Yes	Yes	Yes	Yes
13	Yes	Yes	Yes	Yes
14	Yes	Yes	Yes	Yes
15	No	No	No	No
16	No	No	No	No
17	No	No	No	No
18	Yes	Yes	Yes	No
19		Yes	Yes	Yes
20	Yes	No	Yes	No
21		No	No	No
22		Yes	No	No
23		No	No	No
24	No	No	Yes	No
25	No	No	Yes	No
26	No	No	No	No
27		No	No	No
28	No	No	No	No

beginning of the test. During Visit 1, many locations exhibited a high overall contamination, showing that a number of sites were starting with multiple years of sediment buildup in the fuel storage tank. Visits 3 and 4 showed moderate improvement, with an increase in the number of sites below the limit of 0.05%. Despite this, median values remained well above the ASTM limit, indicating that most systems continued to contain elevated levels of water and sediment.

Table 16. Number of Samples with Visible Water at the Bottom

Visit	# of samples with visible water at bottom	Total Sample Count	Number of Samples with Water (%)
1	7	21	33.3
3	10	27	37.0
4	10	27	37.0
5	9	27	33.3

Qualitative observations of water in bottom samples provide additional context for interpreting these results. As illustrated in Table 16, water was observed in approximately 33% of sites during Visit 1, increasing to 37% during both Visits 3 and 4. The percentage of sites with visible water fell back to 33% in Visit 5, showing that the presence of water was fairly consistent

before or after the introduction of the RD/BD fuel blends.

A majority of the sites with identified free water at the beginning of the study continued to have observed free water through the remainder of the study. A small number of sites, such as Sites 24 and 25, did not have visible water until Visit 4. This could point to water accumulation over time or movement of previously inaccessible water from a fuel delivery. Many of the sites, such as Sites 10 and 11, had observable water at the bottom of the tanks throughout the study.

Overall, while a number of sites showed elevated levels of water and sediment, much of this appears to be because of the preexisting conditions in the storage tanks.

Biological Contamination

Biological contamination exhibited substantial variability across the sampled sites before the introduction of the renewable fuel blend, with values spanning several orders of magnitude. Measured concentrations ranged from 0 to 8334 cATP/mL, indicating the presence of both minimally contaminated and severely impacted systems.

The majority of samples exhibited relatively low cATP levels, with a median value of 3 pg cATP/mL in Visit 1, as shown in Table 17. These values are consistent with low microbial activity and suggest that many systems maintained relatively clean fuel conditions at the time of collection. Moderate contamination was observed in several samples. Three sites had measured cATP values exceeding 100. Two sites in particular (Sites 9 and 18) pointed to extreme contamination, with values of 2358 pg cATP/mL and 8334 pg cATP/mL. These elevated values indicate substantial microbial biomass and likely active microbial growth within those systems.

Table 17. Measured Biological Activity at Selected Sites

Site Number	Visit 1 (pg cATP/mL)	Visit 5 (pg cATP/mL)
1	2.9	0.8
2	2.9	0.8
3	1.92	51.2
4	1.3	1.3
5	179.9	3912.7
6	-	6.7
7	5.6	1809.0
8	3.6	1.9
9	2358.1	1.1
10	18.3	5943
11	2.6	575.6
13	0.0	4.9
14	0.0	4.9
15	1.6	0.8
16	4.9	2.1
17	2.9	0.5
18	8333.6	2.8
19	-	6.0
20	80.6	34.2
21	-	3.1
22	-	1.3
23	-	0.4
24	1.2	628.8
25	1.2	628.8
26	46.2	1.1
27	-	0.2
28	1.2	0.9

The biological contamination levels were measured to be very similar at the end of the study on Visit 5. As seen in Table 18, the average concentration of ATP went from 526 pg cATP/mL during Visit 1 to 505 pg cATP/mL in Visit 5. There was, however, a change in which sites had large levels of ATP. The contamination in Sites 9 and 18 was eliminated by replacing the fuel tanks at these locations.

Table 18. Average, Median, Minimum, and Maximum Biological Activity

	Visit 1 (pg cATP/mL)	Visit 5 (pg cATP/mL)
Average	526.2	504.6
Median	2.9	2.8
Minimum	0.0	0.2
Maximum	8333.6	5943.0

After this change in environment, both sites saw no biological issues. Site 5 had a relatively high concentration of ATP on

Visit 1 (180 pg cATP/mL) and had increased by the end of the study (3913 pg cATP/mL). Some sites, such as Sites 10 and 11, had very low amounts of measured ATP at the beginning of the study and saw a large amount of ATP present by the end of the study. In both cases, water was present at the site from the very beginning of the study.

Overall, the cATP results indicate that microbial growth was not widespread across the monitored renewable diesel and biodiesel blend storage systems but was instead localized to a limited number of tanks. Site-specific storage conditions appear to have been the primary drivers of microbial contamination, with many of these conditions already present before the introduction of the new fuel blends. This pattern is consistent with microbial proliferation occurring only when favorable conditions, such as the presence of free water, are present. This is supported by the data in Table 17, where most samples clustered at very low cATP values while only a few extreme observations accounted for the elevated mean concentrations.

Density

Fuel density varied among the sampling events, reflecting changes in blend composition throughout the field study. As seen in Table 19, Visit 1 exhibited the highest average density (0.851 g/cm^3), whereas Visits 3 and 5 had lower mean densities of 0.815 and 0.818 g/cm^3, respectively.

Table 19. Average, Standard Deviation, Minimum and Maximum Density @ 15 °C Measured on Each Visit

	Visit 1 (g/cm^3)	Visit 3 (g/cm^3)	Visit 5 (g/cm^3)
Average	0.851	0.815	0.818
Standard Deviation	0.015	0.012	0.012
Minimum	0.840	0.804	0.798
Maximum	0.881	0.836	0.841

The higher average and variation in fuel density in Visit 1 correspond with the variable amount of biodiesel present among each site before the introduction of the test fuel. This explains the elevated maximum density observed in Table 19 during Visit 1. The decrease in density between Visit 1 and Visit 3 corresponds with the transition from higher-density biodiesel and No. 2 heating oil blends to fuels containing greater proportions of renewable diesel. Renewable diesel typically exhibits lower density than both No. 2 heating oil and biodiesel.

In comparison to Visit 1, Visits 3 and 5 exhibited narrower distributions of densities, indicating more consistent fuel blending across sampling locations. The minor increase in average density observed between Visits 3 and 5 corresponds to the slight fluctuation in biodiesel content found during Visit 5. This could point to the slight incorrect blending levels of the final RD/BD blend or the possible contamination of the fuel systems with small amounts of No. 2 heating oil. Overall, these measurements support the observed transition toward more uniform RD/BD blends over the course of the field evaluation.

Viscosity

Kinematic viscosity increased modestly throughout the field study, reflecting changes in fuel composition over time. Average viscosity increased from 3.05 mm^2/s in Visit 1 to 3.44 mm^2/s in Visit 3 and 3.56 mm^2/s in Visit 5. As seen in Table 20, Visit 1 exhibited a broader distribution than subsequent visits. This confirms the wide variety of samples during Visit 1, ranging from B0 to B100. The average viscosities for Visits 3 and 5 are much closer, showing greater consistency in fuel viscosity across sampling locations as the study progressed. One sample in Visit 5 was slightly over the viscosity limit.

Table 20. Average, Standard Deviation, Minimum and Maximum Kinematic Viscosity @ 40 °C Measured on Each Visit

	Visit 1 (mm^2/s)	Visit 3 (mm^2/s)	Visit 5 (mm^2/s)
Average	3.05	3.44	3.56
Standard Deviation	0.66	0.26	0.28
Minimum	2.39	2.78	2.88
Maximum	4.29	3.91	4.16

The increase in viscosity from Visit 1 through Visit 5 is consistent with the changes in blend composition observed elsewhere in the study. Because biodiesel has a higher viscosity than renewable diesel, variations in blend ratio are expected to influence the properties of the fuel. Many sites saw a rise in viscosity because they were starting from a less viscous fuel with no biodiesel. The data demonstrate that, while viscosity increased modestly over time, all measured values remained within the range expected for renewable diesel–biodiesel blends suitable for residential heating applications.

Head Coking

The progression of head coking was documented for each Level 1 site, capturing retention head pictures and noting the consistency of the deposits. While an attempt was made to capture an image of the retention head at every visit, it was not possible in some cases for burners with fixed retention heads. However, all head conditions were captured during Visit 5, including those at the nineteen Level 2 sites. In this section, the condition of the retention head for each site from Visit 5 is shown. The sites are grouped by appliance type and generalized combustion chamber configuration, as described below:

- **Hot chamber boilers**: These are typically known as single pass boilers with refractory material present that retains and reflects heat in the combustion chamber
- **Cold chamber boilers:** Otherwise known as triple-pass boilers with little to no refractory material which causes the combustion chambers to be cooler than the other appliance types listed
- **Furnaces:** Refractory material forms the entire combustion chamber in furnaces and, hence, the chamber temperatures are some of the hottest compared to other appliance types
- **Water heaters:** Standalone water heaters are also known to have very hot chambers as the lining is entirely made of refractory material

The importance of grouping by appliance type is highlighted by results from the separate NORA in-lab *Head Coking Project.* The preliminary findings of the study indicate that differences in combustion chamber temperature based on appliance type strongly impact the amount of head coking produced. Additionally, this study suggests several other factors can influence the amount of head coking. Additional information is provided for each picture for context.

Each picture is also graded based on a H*ead Coking Grading Scale* (see Appendix B) formulated by the research team and reviewed by industry experts for accuracy. The scale determines a rating for head coking from 0 (no head coking) to 5 (worst-case scenario) based on the severity of the deposit buildup. In some cases, half ratings were given because the amount and severity of deposits did not fully fit into a rating category. Moreover, some ratings were elevated by one grade point if the deposit material was tacky (difficult to remove) in nature as opposed to flaky (easy to remove).

The retention heads with a coking grade of three or higher were cleaned during the first visit to their respective sites to establish a standard baseline condition for the remainder of the test. In some cases, the attending technician cleaned the head at subsequent visits even when a cleaning was not required because of company standard practices. Note: in the figures below, the site number labels are followed by a 0-5 rating. These correspond to the Head Coking Grading Scale found in Appendix B.

The practical impact of observed head coking and a comparison with traditional heating oil are presented in the “Discussion” section of this report.

Hot Chamber Boilers

There were ten Level 1 sites with hot chamber boilers. While these sites are grouped together, the amount of refractory material inside the chamber and the average combustion chamber temperatures varied between specific appliances. The retention heads at each sites during Visit 5 with hot chamber boilers are shown in Figure 4.

Figure 4. Photos of the retention heads from Level 1 sites with hot chamber boilers during visit period 5. The number after the dash indicates the coking level score.



The heads at Sites 7, 9, and 18 have not been cleaned in several years. The heads at Sites 10 and 26 were not cleaned during the entirety of the test period. Only the head at Site 15 was cleaned during Visit 3. A new retention head was installed at Site 27 on 12/5/25, approximately six weeks prior to Visit 4. During Visit 4, none of the retention heads in this group were cleaned.

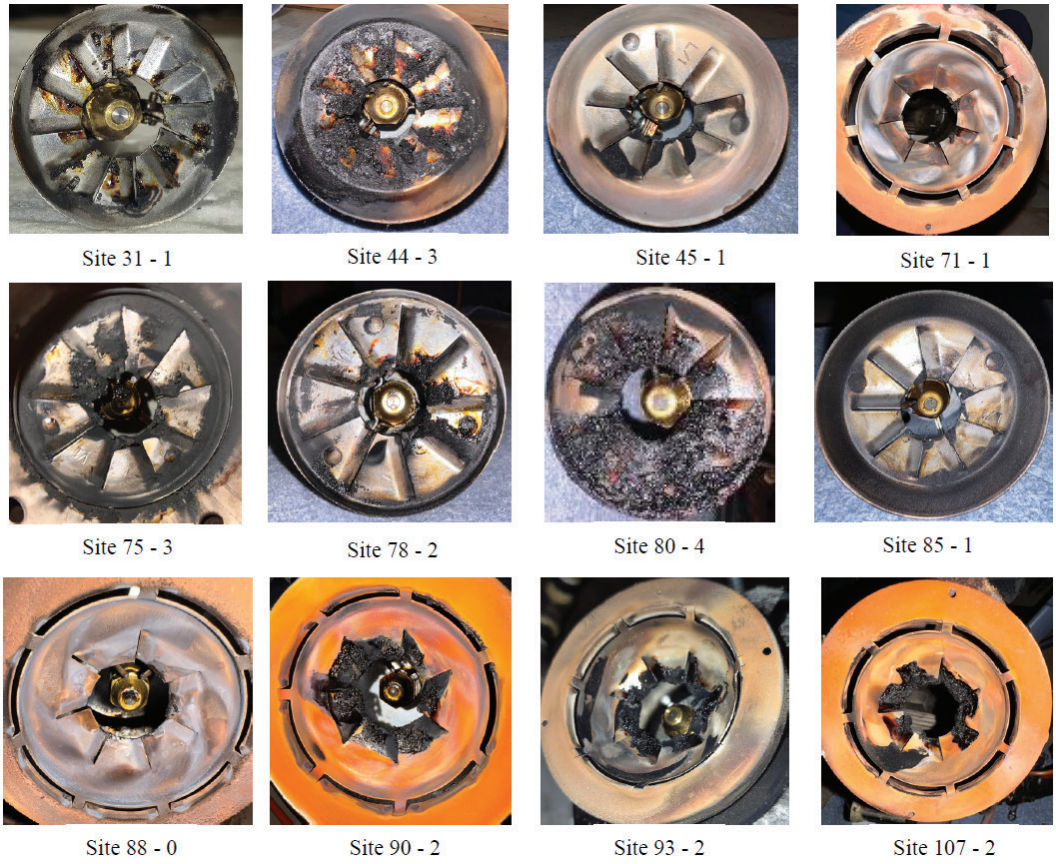
Flue gas O_2 at Sites 9, 15, and 17 indicated combustion that was leaner than is typically recommended by burner manufacturers. Measured CO at each of these sites was less than 10 ppm, so the excess air was not adjusted. At the remaining Level 1 sites with hot chamber boilers, the O_2 readings were within typical specifications.

Out of the nineteen Level 2 sites chosen for data collection during Visit 5, a total of twelve contained hot chamber boilers. The head pictures from those sites are shown in Figure 5.

The heads from Sites 44 and 45 were cleaned in September 2025 while the head from Site 80 was cleaned in October 2025. All three sites operated throughout the 2025/26 heating season with a cleaned head. It is not known when the heads at Sites 31 and 85 were last cleaned. The heads at the remaining sites shown in Figure 5 have not been cleaned for several years. The O_2 readings at all sites were within typically acceptable parameters except Sites 31 (lean) and 93 (rich). At both sites, CO was below 10 ppm. Therefore, the combustion air was not adjusted at either site. The CO reading at Site 45 was measured to be 35 ppm.

The average pump pressure across all visited sites with hot chamber boilers was 120 psi.

Figure 5. Photos of the retention heads from select Level 2 sites with hot chamber boilers during visit period 5. The number after the dash indicates the coking level score.



Cold Chamber Boilers

A total of nine sites with cold chamber boilers were examined during Visit 5. Eight of these were Level 1 sites and one was Level 2. The head conditions from Visit 5 to each of the sites with colder chamber boilers are shown in Figure 6.

The average measured pump pressure at sites with cold chamber boilers was 166 psi. Flue gas O_2 at Sites 1, 20, 23, and 95 was lower than the typically recommended level, resulting in rich combustion. At each of these sites, the CO measured was 22 ppm or lower. The attending technician opted to adjust the excess air to achieve leaner combustion at Site 23 only. The excess-air settings at the remaining sites were left unchanged. The O_2 at all other visited sites with cold

Figure 6. Photos of the retention heads from all sites with cold chamber boilers during visit period 5. The number after the dash indicates the coking level score.

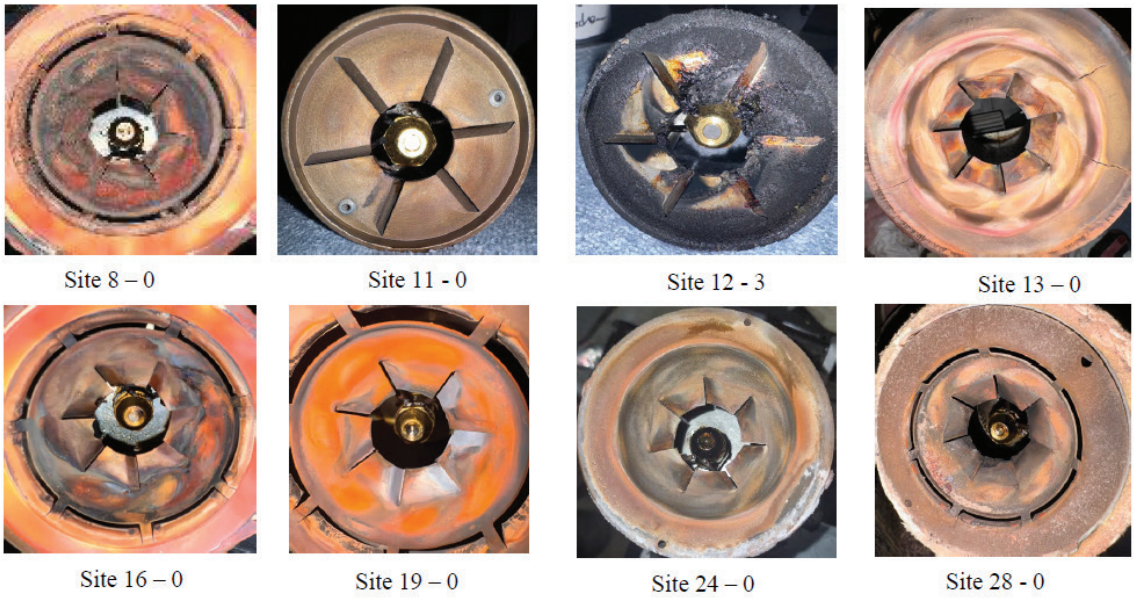


chamber boilers was within the typically acceptable range. New retention heads were installed at Sites 1, 21, and 23 during the first week of November 2025, at Site 22 in January 2026, and at Sites 2 and 4 in February 2026. The head at Site 6 was cleaned in January 2026 while the head at Site 20 was cleaned in April 2025. It is not known when the head at Site 95 was last cleaned.

Furnaces

There were eight Level 1 sites with furnaces. The retention heads from Visit 5 to each of the sites with furnaces are shown in Figure 7.

Figure 7. Photos of the retention heads from Level 1 sites with furnaces during visit period 5. The number after the dash indicates the coking level score.



During Visit 5, the combustion readings at each of the sites indicated acceptable O_2 and CO according to the respective burner manufacturers' specifications except at Sites 16 (rich) and 24 (lean). At both sites, the attending technician decided to leave the combustion parameters unchanged since the measured CO was very low. The retention heads at all sites except Site 12 have not been cleaned in several years. A new retention head was installed at Site 11 in November 2025.

Six Level 2 sites with furnaces were also visited during this period. The head conditions at those sites are shown in Figure 8.

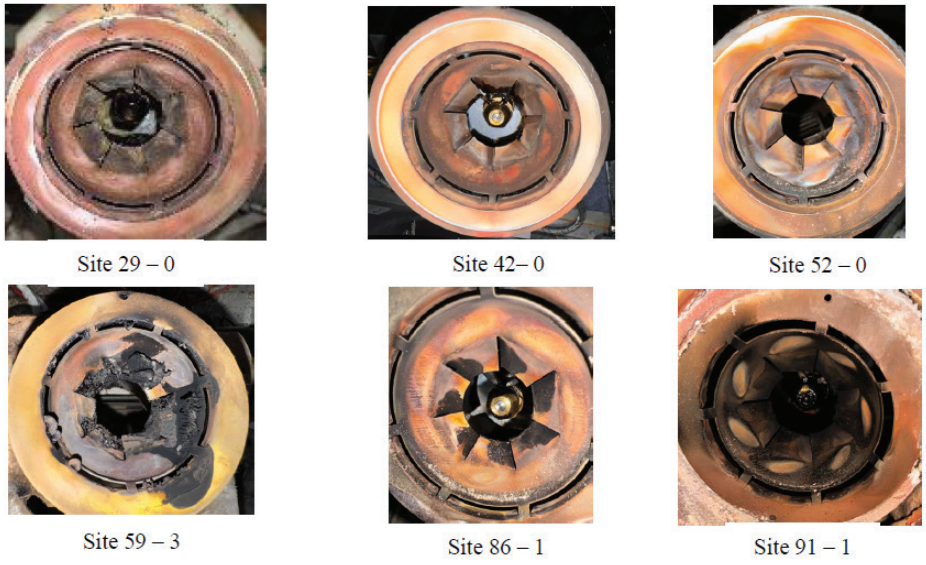


Figure 8. Photos of the retention heads from Level 2 sites with furnaces during visit period 5. The number after the dash indicates the coking level score.

The furnace at Site 59 was installed in January 2025. The head at that site has not been cleaned since then. For the remaining sites, the heads most likely have not been cleaned for several years prior to the visits. All sites except Site 59 (rich) were found to have acceptable values for flue gas O_2 and CO. At Site 59, the CO was found to be greater than 100 ppm. The excess air was adjusted to obtain a CO reading less than 10 ppm. The average pump pressure across all visited sites with furnaces was 117 psi.

Water Heaters

There were two Level 1 sites with water heaters. The retention heads from Visit 5 to each of these are shown in Figure 9.

Figure 9. Photos of the retention heads from sites with water heaters during Visit 5. The number after the dash indicates the coking level score.



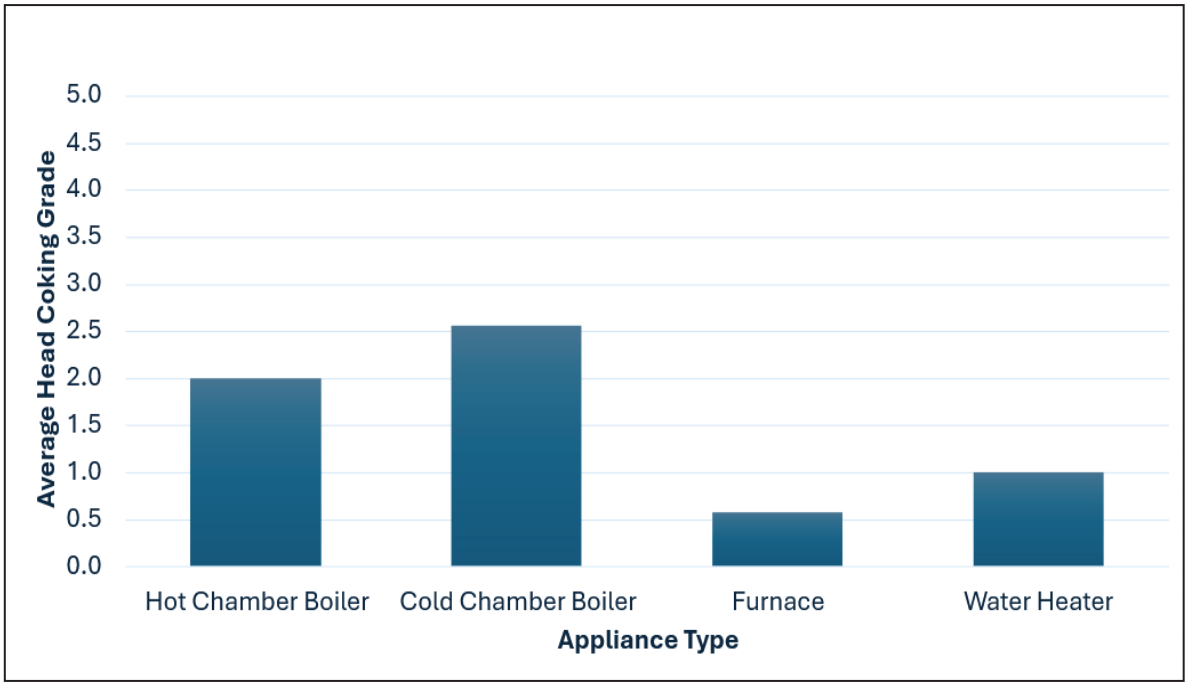
Site 14 – 2 Site 25 – 0

Flue gas O_2 at Site 14 consistently remained greater than the upper limit set by the appliance manufacturer during the test period (~7.5% O_2 as opposed to ~5.9%). The same was observed at Site 25 during Visits 1 and 2, but excess air was later adjusted to obtain O_2 readings within specifications. The head at Site 25 was cleaned in March 2025.

The average measured pump pressure at sites with water heaters was 128 psi.

The average of all head coking grades from Visit 5 was calculated for each appliance type. The comparison is shown in Figure 10.

Figure 10. Average head coking grades for each appliance type from Visit 5.



Discussion

This field study followed a bold plan to include a very wide range of heating appliance types and neither emptied nor cleaned the fuel tanks prior to the start of delivery of the test fuels. Many of the systems have been in place for more than 20 years. The project team felt this approach was an important reflection of what a realistic widespread adoption would be. Liquid heating marketers typically do not have the capability to economically deliver different fuels to segmented parts of their customer base. Conversion of heating systems and/or emptying and cleaning tanks before the transition is simply unrealistic.

The wide range of appliance types included cold chamber boilers where the flame can freely radiate heat to the metal, water-cooled surrounding surfaces, hot chamber boilers in which the flame is surrounded by insulating refractory and then the boiler wall, furnaces which have hot refractory lined chambers cooled only by air, and water heaters which typically have compact, uncooled chambers. All of the major burner types in the U.S. were included.

Even under these challenging conditions, none of the sites experienced problems with ignition, steady-state combustion, fuel-system leaks, or chimney blockages. At four sites, the burner's primary controls were outdated. This was resolved through upgrades to modern controls. Based on prior NORA lab experience, these might have been addressed by adjusting the air/fuel ratio on the burner to a slightly richer setting. With an interest in getting the system operating as quickly as possible, this was not explored at these sites.

At Sites 9 and 18, a high concentration of ATP indicating strong biological contamination was found in the tanks. The research team strongly believes that this was due to conditions that existed prior to the start of this test and was not related to the test fuel. Free water was found at the bottom of these tanks. The fuel marketer decided to replace the tank at Site 18 due to this issue. No fuel-related issues occurred at this site throughout the test period. The homeowner at Site 9 changed their tank as a proactive measure as it was more than 50 years old. The pump at this site failed in March 2026. The failure was attributed to normal mechanical wear after more than 20 years of operation (exact age unknown) and exposure to fuel particulates before the tank was replaced.



Broco Energy rail, storage and truck terminal, Haverhill, MA

In the examination of burner head coking, the results strongly showed that "colder" chamber boilers had more coking than hot chamber applications such as warm air furnaces and water heaters. This is consistent with prior studies conducted at the NORA research lab. With cold chamber boilers, there seems to be somewhat more head coking than is normally observed with No. 2 heating oil.

In the remainder of the appliances, head coking can be considered to be the

same or similar to that observed with No. 2 heating oil. In all cases, the burner performance was not impacted by the observed burner head coke. Burner manufacturers recommend at least annual head cleaning by a qualified professional, and if followed, no concerns would be expected in all the cases studied.

Figure 10, in the prior section, presents the average head coking score from Visit 5 for each appliance type. This is based on the numerical scale for head coking that was developed by NORA (see Appendix B). Based on the project team's experience, a head-coking rating of 2 or lower would typically be expected after one year of operation with No. 2 heating oil. It is interesting to note that no significant differences in head coking between the RD50/B50 blends and the RD80/B20 blends were observed.

The main driver of fuel stability appears to be the environment the fuel is subjected to over time, regardless of the fuel being used. For example, a number of sites had visible water collected in Visit 1 before the introduction of the RD80/B20 or RD50/B50 blends. At two sites, a high concentration of ATP, indicating strong biological contamination, was found. One of these contaminated sites, Site 18, showed an acid number increase to 0.96 mg KOH/g, well over the ASTM D396 limit of 0.3 mg KOH/g. This indication of fuel degradation is counter to the stable levels observed at most other site locations.

The summer shutdown period also seems to be the most vulnerable period for the fuel blends, as it is with typical No. 2 heating oil. Sites 6 (RD50/B50) and 9 (RD80/B20) both showed a large decrease in oxidative stability between Visits 2 and 3. Site 9 also experienced a large increase in the measured total acid number during this same period. However, in both cases, the oxidative reserve and acid number values came into line with the ASTM D396 standards by Visit 4. This may highlight the improvement that occurs in a fuel system when it receives fresh fuel during the heating season.

Conclusions

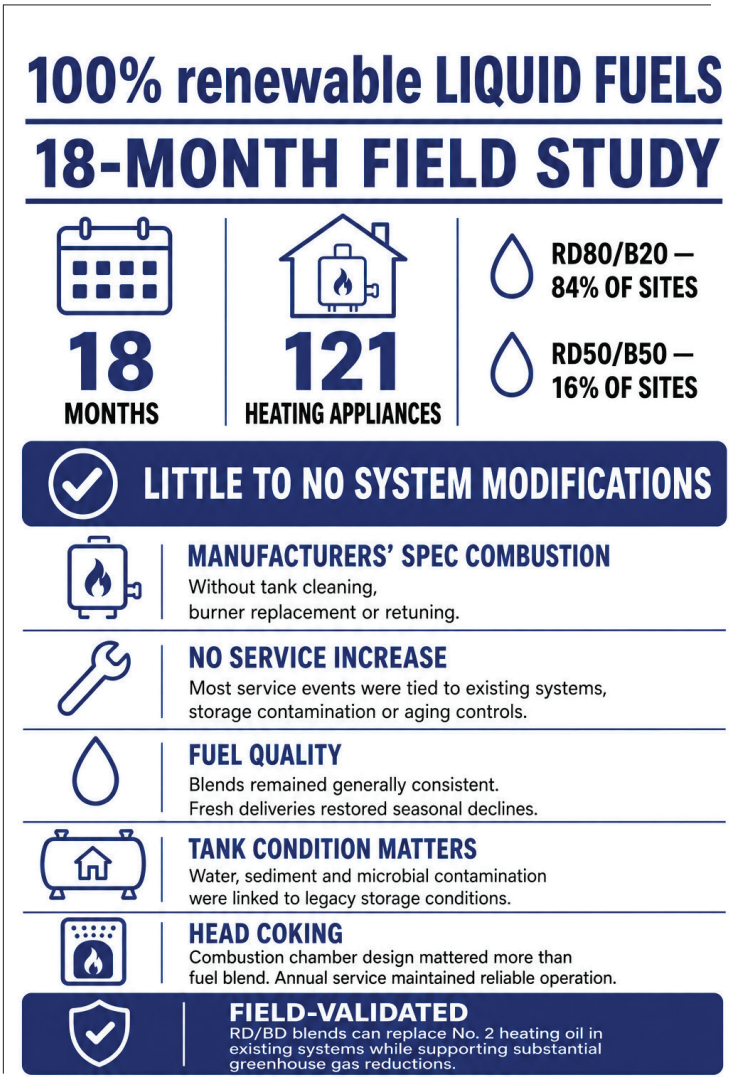
This eighteen-month field study demonstrates that 100% renewable liquid fuel blends consisting of RD50/B50 and RD80/B20 can be successfully used in a broad cross-section of existing residential and light commercial oilfired heating appliances, with few or no system modifications.

Across 121 boilers, furnaces, and water heaters, combustion performance remained within manufacturers' specifications after the switch from conventional heating oil with three exceptions, even though the tanks were not cleaned and the burners were neither replaced nor retuned beforehand. Approximately 16% of the sites utilized RD50/B50, and the remaining sites used RD80/B20. For this reason, the conclusions are weighted towards RD80/B20 results.

The fuels performed reliably under realistic field conditions representative of a large-scale market transition. The nature and cause of service calls showed no meaningful increase in fuel-related maintenance with the renewable fuels, as compared with previous operation. The limited service events that did occur were primarily attributable to existing heating system conditions, legacy storage tank contamination, or aging controls rather than the renewable fuels themselves. Four controls were replaced with current-generation models designed to respond to less luminous flames.

Fuel quality monitoring indicated that blend composition remained generally consistent throughout the project. Although oxidative stability declined and acid number increased at some locations following the summer storage period, fresh fuel deliveries restored fuel quality to acceptable levels during the heating season. Most measured fuel quality concerns were site-specific and correlated with pre-existing storage conditions, including water accumulation and microbial contamination that were already present before the introduction of the renewable fuels.

The study confirms that storage tank condition remains a more significant determinant of long-term fuel quality than fuel composition itself. Importantly, the occurrence of water, sediment, and microbial contamination was not uniformly distributed across the study population. Instead, these issues were concentrated at specific locations and often persisted throughout multiple sampling events. Elevated water, sediment, and biological contamination were associated with legacy storage issues rather than the RD/BD blends, reinforcing the importance of established tank maintenance practices regardless of the fuel used. Storage tank condition remains the dominant factor governing long-term fuel quality performance.



Evaluation of burner head coking showed that combustion chamber design had a much greater influence on head coking than did the fuel blend. Cold-chamber boilers ("triple pass" without a chamber liner) exhibited the highest degree of head coking, whereas furnaces and water heaters showed little or no significant head coking. Hot-chamber boilers (cast iron boilers with refractory chamber liners) also showed little head coking. Even where increased deposits were observed, burner performance remained acceptable, and routine annual service was sufficient to maintain reliable operation. No meaningful difference in head coking was observed between the RD50/B50 and RD80/B20 blends.

Overall, the results provide strong field validation that renewable diesel/biodiesel blends can serve as practical replacements for No. 2 heating oil in existing systems. The findings support widespread adoption of these renewable fuels as a technically viable pathway toward substantial greenhouse gas reductions without requiring extensive replacement of heating appliances or costly system-wide changes for customers. Continued emphasis on proper storage tank maintenance, routine burner service, and use of modern burner controls will further support reliable long-term operation as adoption of 100% renewable liquid heating fuels expands.

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APPENDICES

Appendix A.

Table A1. Certificate of Analysis provided for the BD 100 used in the tested blends

Property		Value	ASTM D6751 Limit	Units	Test Method (current revision)
Cloud point:		4.3	Report	**°C**	D5773
Free Glycerin:		0.002	0.020, max	**% mass**	D6584
Total Glycerin:		0.030	0.240, max	**% mass**	D6584
Monoglycerides[1]:		0.106	N/A	**% mass**	D6584
Diglycerides[1]:		0.000	N/A	**% mass**	D6584
Triglycerides[1]:		0.000	N/A	**% mass**	D6584
Water & Sediment:		0.000	0.050, max	**% volume**	D2709
Acid Number:		0.28	0.50, max	**mg KOH/g**	D664
Visual Inspection[1]:		1.0	N/A	**Haze rating**	D4176, Procedure 2
Relative Density at 60°F[1]:		0.8830	N/A	**N/A**	D1298
Oxidation Stability (110 °C):		09.6	3, min	**hrs.**	EN15751
Flash point (closed cup):		177.5	93, min	**°C**	D93
Alcohol Control	**Option 1: Methanol**	N/A	0.2, max	**% mass**	*EN 14110*
	Option 2: Flashpoint	177.5	130, min	**°C**	D93
Moisture[1]:		0.010	N/A	**% mass**	D6304
Cold Soak Filtration:		91	360	**seconds**	D7501
Cold Soak Filter Blocking Tendency[1]:		1.00	N/A	**N/A**	CAN/CGSB-3.0 No. 142.0
Sulfur:		2.2	15	**ppm (mg/kg)**	D7039
Sodium & Potassium Combined:		< 0.2 *	4.0 (total)	**ppm (mg/kg)**	*EN 14538*
Calcium & Magnesium Combined:		< 0.2 *			
Total Contamination[1]:		0.2 *	N/A	**mg/L**	D7321
Ester Content[1]:		98.6 *	N/A	**% mass**	*EN 14103*
Phosphorus:		0.0000 *	0.001, max	**% mass**	D4951
Carbon Residue:		0.000 *	0.050, max	**% mass**	D4530
Sulfated Ash:		0.005 *	0.020, max	**% mass**	D874
Kinematic Viscosity at 40 °C:		4.247 *	1.9 - 6.0	**mm²/sec.**	D445
Copper Corrosion (3 hrs. at 50 °C):		1A *	No. 3, max	**N/A**	D130
Distillation at 90% Recovered:		352.0 *	360, max	**°C**	D1160
Cetane Number:		55 *	45, min	**N/A**	D613

[1] These tests are not ASTM D6751 specification requirements.

* This value is the most recently acquired result for this product from this plant. This test is performed

Table A2. Certificate of Analysis provided for the RD 100 used in the tested blends

Property	Value	ASTM D975 No. 2-D Limit	Units	Test Method (current revision)
Cloud point:	-12	Report	**°C**	D5771
Water & Sediment:	<0.02	0.05, max	**% volume**	D2709
Conductivity:	68	25, min	**pS/m**	D2624
Appearance:	Clear & Bright	Clear & Bright	**N/A**	D4176, Procedure 1
API Gravity @ 60°F:	49.16	N/A	**N/A**	D4052
Specific gravity @ 60°F:	0.7832	N/A	**N/A**	D4052
Flash point:	63	52, min	**°C**	D93A
Total Sulfur:	<1	15, max	**ppm (mg/kg)**	D5453
Ramsbottom Carbon:	0.05	0.35, max	**% mass**	D524
Ash:	<0.001	0.01	**% mass**	D482
Kinematic Viscosity at 40°C:	3.225	1.9 – 4.1	**mm^2/sec**	D445
Copper Corrosion (3 hrs at 50°C):	1a	No. 3	**N/A**	D130
Distillation Temperature, at 90%:	309.0	282 – 338	**°C**	D86
Cetane Index:	95.4	40, min	**N/A**	D4737, Procedure A
***Lubricity, HFRR @ 60°C**	370	520, max	micron	ASTM D6079

Appendix B.
BURNER HEAD COKING SCALES

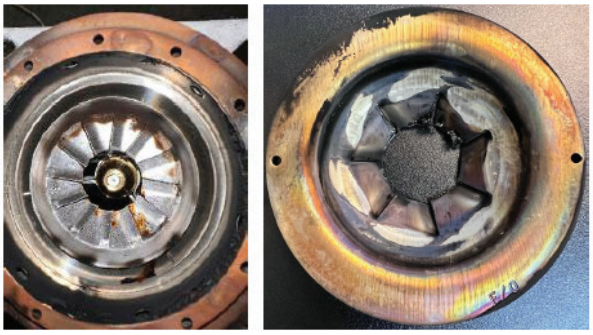
NORA created the head coking scale to quantify the severity of carbon buildup on burner retention heads in the field. The guidelines on the methodology and usage of the scale are given below:

- The rating begins at 0, the lowest amount of coking and goes up to 5, which has the greatest amount of coking.
- In some cases, the head condition may not fit into a rating. In those instances, a half rating (e.g., 1.5) can be used.
- The scale does not judge the consistency (powder-like or gummy/tacky consistency) of the buildup. If the buildup on the head is primarily gummy, the rating can be increased by 1 unless it is judged to be level 5.

Rating of 0

This rating describes heads with little to no coking. There is no blockage of any air slots. Some areas of minimal deposits can exist, but they cannot protrude outward from the head. Examples of heads with a rating of 0 are shown in Figure B-1.

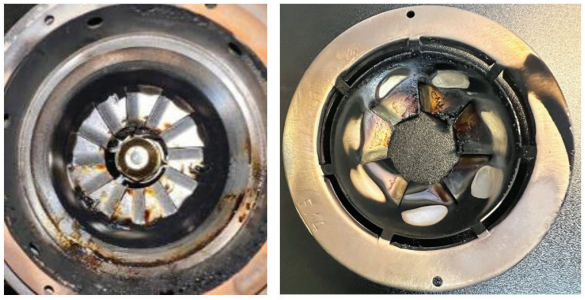
Figure B-1. Examples of retention heads with a rating of 0



Rating of 1

This rating describes light coking with buildup areas beginning to form on multiple fins and the outer rim (if applicable) of the head. The buildup may be starting to form protrusions on the fins. There should be no blockage of air slots in this rating.

Figure B-2. Examples of retention heads with a rating of 1



Rating of 2

Heads with a rating of 2 will show areas of buildup that protrude outward from the face of the head. The secondary and tertiary slots are mostly open, but some blockages are beginning to emerge. Examples of heads with a rating of 2 are shown in Figure B3.

Figure B-3. Examples of retention heads with a rating of 2

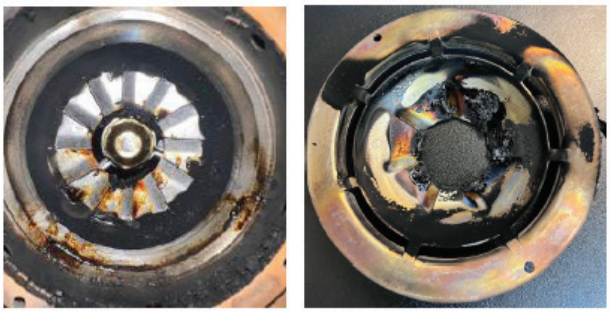


Figure B-4. Examples of retention heads with a rating of 3



Rating of 3

Heads with this rating will need to be cleaned and cannot be left as found. There are several areas of protruding buildup, and almost all secondary slots have some blockage, although each slot will remain mostly open. Tertiary slot blockage is also present in this case.

Figure B-5. Example of retention head with a rating of 4



Rating of 4:

Several large areas of buildup are present on a head with a rating of 4. There is substantial blockage of secondary and/or tertiary air slots. Some of the buildup areas are beginning to join and form clusters. Elevated CO at startup may be observed. These heads should be cleaned and corrective measures taken to reduce such head coking.

Figure B-6. Examples of retention heads with a rating of 5



Rating of 5

Heads with a rating of 5 will have large clusters of deposits that will block most air pathways. Elevated CO and smoke number up to 3 on the Bacharach scale can be expected. A new head should be installed, all burner parts with deposits should be cleaned, and corrective changes should be made.

Appendix C.
FUEL TESTING DATA

Table C1. Biodiesel Content Measured on Each Visit

Site Number	Visit 1 (%)	Visit 2 (%)	Visit 3 (%)	Visit 4 (%)	Visit 5 (%)
1	100.0	49.2	49.7	50.9	49.6
2	100.0	49.2	49.7	50.9	49.6
3	92.3	50.4	49.0	48.6	40.1
4	94.5	49.5	48.3	49.8	39.2
5	60.9	49.8	38.9	45.2	48.7
6	-	48.8	47.5	49.2	48.8
7	2.7	19.0	18.8	12.0	23.1
8	1.1	18.9	18.3	19.1	15.4
9	2.5	17.6	17.1	9.9	22.6
10	17.9	-	19.8	19.2	24.6
11	18.5	19.7	19.9	19.2	22.0
12	-	18.2	-	19.0	22.2
13	17.6	19.9	19.6	19.3	23.8
14	17.6	19.9	19.6	19.3	23.8
15	17.4	19.0	19.3	12.8	19.9
16	4.1	19.0	19.0	12.0	17.9
17	0.0	19.2	18.8	5.1	6.3
18	0.0	17.9	18.8	13.8	11.3
19	-	16.8	16.8	18.7	23.9
20	0.0	7.8	8.3	14.6	14.6
21	-	19.5	19.2	19.6	19.1
22	-	19.2	19.9	19.4	2.9
23	-	19.3	19.4	19.4	18.5
24	0.0	19.0	19.3	19.5	19.3
25	0.0	19.0	19.3	19.5	19.3
26	0.0	19.5	8.5	21.5	24.5
27	-	18.7	19.9	10.7	13.6
28	0.0	-	-	29.8	25.1

Table C2. Oxidative Reserve Measured for Each Visit

Site Number	Visit 1 (hrs)	Visit 2 (hrs)	Visit 3 (hrs)	Visit 4 (hrs)	Visit 5 (hrs)
1	3.1	10.0	8.4	2.8	13.7
2	3.1	10.0	8.4	2.8	13.7
3	10.1	0.6	9.0	15.0	14.3
4	8.0	10.0	8.6	13.2	6.6
5	2.5	6.8	4.0	5.3	8.3
6	-	9.8	1.0	16.8	15.6
7	19.3	12.6	13.6	9.5	3.9
8	14.6	13.7	1.7	4.4	4.3
9	13.7	18.5	0.7	12.5	6.2
10	12.1	-	3.8	3.8	6.7
11	9.6	20.7	9.9	5.1	8.2
12	-	2.5	-	2.5	2.7
13	10.7	26.8	7.4	6.8	7.9
14	10.7	26.8	7.4	6.8	7.9
15	10.9	19.0	0.6	14.0	6.8
16	7.5	24.0	2.3	18.8	8.2
17	10.7	6.6	7.6	19.7	13.1
18	>20.0	4.8	6.7	9.4	8.4
19	-	12.7	3.9	3.0	2.2
20	15.4	17.2	9.2	11.6	15.6
21	-	14.4	9.9	4.4	21.1
22	-	-	13.3	14.5	22.4
23	-	14.9	15.6	7.1	13.1
24	>20.0	16.5	7.3	8.8	10.3
25	>20.0	16.5	7.3	8.8	10.3
26	>20.0	7.2	2.6	6.4	6.1
27	-	19.4	7.4	4.8	9.9
28	>20.0	-	-	4.6	5.4

Table C3. TAN Measured for Each Visit

Site Number	Visit 1 (mg KOH/g)	Visit 2 (mg KOH/g)	Visit 3 (mg KOH/g)	Visit 4 (mg KOH/g)	Visit 5 (mg KOH/g)
1	0.36	0.22	0.23	0.20	0.17
2	0.36	0.22	0.23	0.20	0.17
3	0.26	0.19	0.24	0.20	0.13
4	0.30	0.33	0.24	0.22	0.14
5	0.68	0.29	0.36	0.31	0.27
6	-	0.17	0.24	0.23	0.14
7	0.13	0.23	0.41	0.10	0.17
8	0.06	0.19	0.13	0.12	0.12
9	0.31	0.27	1.30	0.12	0.14
10	0.10	-	0.23	0.13	0.16
11	0.12	0.22	0.13	0.13	0.13
12	-	0.24	-	0.17	0.20
13	0.09	0.16	0.17	0.13	0.14
14	0.09	0.16	0.17	0.13	0.14
15	0.09	0.17	0.19	0.12	0.12
16	0.06	0.16	0.13	0.10	0.16
17	0.06	0.17	0.17	0.09	0.06
18	0.05	0.96	0.15	0.11	0.13
19	-	0.19	0.24	0.22	0.26
20	0.10	0.22	0.30	0.20	0.27
21	-	0.12	0.22	0.15	0.10
22	-	-	0.24	0.15	0.09
23	-	0.19	0.19	0.13	0.19
24	0.03	0.12	0.41	0.17	0.14
25	0.03	0.12	0.41	0.17	0.14
26	0.04	0.13	0.12	0.15	0.16
27	-	0.14	0.19	0.10	0.09
28	0.05	-	-	0.17	0.14

Table C4. Bound Water Content Measured for Each Visit

Site Number	Visit 1 (ppm)	Visit 2 (ppm)	Visit 3 (ppm)	Visit 4 (ppm)	Visit 5 (ppm)
1	244	161	215	252	214
2	244	161	215	252	214
3	196	58	120	122	173
4	196	50	160	103	268
5	135	285	1781	438	451
6	-	49	202	204	202
7	15	119	228	62	185
8	54	106	116	42	85
9	58	129	314	36	126
10	133	-	258	32	226
11	142	144	287	120	174
12	-	-	-	-	-
13	120	184	159	41	300
14	120	184	159	41	300
15	88	115	108	33	128
16	52	148	314	41	100
17	18	191	125	23	66
18	28	184	154	91	68
19	-	138	230	239	460
20	39	9	135	54	103
21	-	58	90	49	139
22	-	47	65	43	55
23	-	43	86	43	115
24	28	58	193	65	878
25	28	58	193	65	878
26	64	93	89	44	242
27	-	121	144	29	96
28	17	-	-	88	144

Table C5. Water and Sediment Content Measured for Each Visit

Site Number	Visit 1 (% vol.)	Visit 3 (% vol.)	Visit 4 (% vol.)	Visit 5 (% vol.)
1	<0.005	0.005	0.01	>0.5
2	<0.005	0.005	0.01	>0.5
3	0.5	0.2	0.1	0.2 (water)
4	0.3	0.05	0.01	0.5
5	>0.5	>0.5 (water)	>0.5 (water)	>0.5 (water)
6	-	0.01	0.01	0.3 (water)
7	>0.5	>0.5 (water)	>0.5	0.01
8	>0.5	0.01	>0.5	0.5 (water)
9	>0.5	>0.5 (water)	0.05	0.05
10	>0.5 (water)	0.4 (water)	>0.5 (water)	>0.5 (water)
11	>0.5 (water)	>0.5 (water)	>0.5 (water)	>0.5 (water)
12	-	-	-	-
13	>0.5 (water)	0.4 (water)	0.4 (water)	0.1 (water)
14	>0.5 (water)	0.4 (water)	0.4 (water)	0.1 (water)
15	>0.5	0.3	0.05	0.05
16	0.4	0.05	>0.5	0.05
17	0.01	0.01	0.01	0.01
18	>0.5 (water)	0.05 (water)	0.01 (water)	0.005
19	-	>0.5 (water)	>0.5 (water)	0.5 (water)
20	>0.5 (water)	0.05	0.2 (water)	0.01
21	-	0.2	0.01	0.01
22	-	0.5 (water)	0.2	0.01
23	-	0.02	0.02	0.2
24	>0.5	>0.5	0.4 (water)	>0.5
25	>0.5	>0.5	0.4 (water)	>0.5
26	0.2	0.01	0.05	0.05
27	-	0.4	0.2	0.01
28	0.1	-	0.05	0.02

Table C6. ATP Concentration Measured for Each Visit

Site Number	Visit 1 (pg cATP/mL)	Visit 3 (pg cATP/mL)	Visit 4 (pg cATP/mL)	Visit 5 (pg cATP/mL)
1	2.9	-	-	0.8
2	2.9	-	-	0.8
3	1.9	-	-	51.2
4	1.3	-	-	1.3
5	179.9	877.7	98.1	3912.7
6	-	-	-	6.7
7	5.6	978.6	-	1809.0
8	3.6	-	-	1.9
9	2358.1	160.2	-	1.1
10	18.3	6.1	5.3	5943.0
11	2.6	7.8	59.2	575.6
12	-	-	-	-
13	0.0	1.4	7.1	4.9
14	0.0	1.4	7.1	4.9
15	1.6	-	-	0.8
16	4.9	-	-	2.1
17	2.9	-	-	0.5
18	8333.6	364.2	-	2.8
19	-	54.0	29.2	6.0
20	80.6	-	4.5	34.2
21	-	-	-	3.1
22	-	0.7	-	1.3
23	-	-	-	0.4
24	1.2	-	-	628.8
25	1.2	-	-	628.8
26	46.2	-	-	1.1
27	-	-	-	0.2
28	1.2	-	-	0.9

Table C7. Density Measured for Each Visit

Site Number	Visit 1 (g/cm^3)	Visit 3 (g/cm^3)	Visit 5 (g/cm^3)
1	0.881	0.834	0.835
2	0.881	0.834	0.835
3	0.877	0.834	0.839
4	0.879	0.832	0.840
5	0.869	0.836	0.841
6	-	0.833	0.836
7	0.842	0.805	0.809
8	0.840	0.806	0.800
9	0.842	0.811	0.808
10	0.847	0.806	0.814
11	0.851	0.806	0.811
12	-	0.812	0.816
13	0.847	0.811	0.811
14	0.847	0.811	0.811
15	0.843	0.805	0.806
16	0.842	0.811	0.803
17	0.844	0.806	0.826
18	0.843	0.807	0.798
19	-	0.810	0.811
20	0.840	0.826	0.814
21	-	0.805	0.809
22	-	0.805	0.816
23	-	0.804	0.817
24	0.840	0.805	0.812
25	0.840	0.805	0.812
26	0.840	0.827	0.819
27	-	0.805	0.830
28	0.844	-	0.815

Table C8. Viscosity Measured for Each Visit

Site Number	Visit 1 (mm^2/s)	Visit 3 (mm^2/s)	Visit 5 (mm^2/s)
1	4.29	3.80	3.88
2	4.29	3.80	3.88
3	4.14	3.66	3.71
4	4.29	3.78	3.98
5	3.66	3.32	4.16
6	-	3.75	4.01
7	2.76	3.39	3.51
8	2.56	3.41	3.51
9	2.61	3.30	3.52
10	3.02	3.49	3.51
11	2.86	3.39	3.52
12	-	3.49	3.63
13	2.89	3.27	3.59
14	2.89	3.27	3.59
15	2.92	3.38	3.70
16	2.67	3.91	3.50
17	2.95	3.53	3.04
18	2.82	3.31	3.51
19	-	3.35	3.51
20	2.39	2.78	3.24
21	-	3.48	3.59
22	-	3.47	3.29
23	-	3.42	3.27
24	2.47	3.48	3.55
25	2.47	3.48	3.55
26	2.45	2.82	3.48
27	-	3.38	2.88
28	2.60	-	3.57

Appendix D.

BIODIESEL CONTENT CHANGE

FROM PAGE 15



Figure 3. Biodiesel content change between Visits 1 and 2, showing the sites reaching the desired biodiesel levels.



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