Auto-Ignition of Cooking Oils

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Abstract

The ignition of cooking oils plays a large role in the problem of residential fires. While cooking is a leading cause of residential fires at 40%, an estimated 2/3rds of cooking fires begin with ignition of the cooking oil. The background behind the rationale for studying this topic and the broader context are introduced with national fire statistics. These emphasize the importance of the need to understand cooking oil fires, specifically the ignition characteristics of common household cooking oils.

Past experiments were researched to give insight into the temperatures ranges at which cooking oil will auto-ignite. Then a repeatable experimental procedure was designed to test the auto-ignition temperatures of liquid cooking oils. The oils tested were canola oil, vegetable oil, and olive oil. The experiment was also expanded to also test butter and margarine using a slightly modified procedure. In addition to auto-ignition, the flame point of canola oil was also tested.

The auto-ignition temperatures for the oils were determined to be as follows: canola oil: 424℃, vegetable oil: 406 ℃ and olive oil: 435℃. The flame point of canola oil was at 379 ℃.The auto-ignition temperature for Smart Balance was 432 ℃, and the butter did not auto-ignite.

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Background

The Fire Problem

Everyone should feel safe at home, but residential fires are considerably the most destructive type of fire. According to reported fire statistics from the U.S. Fire Administration, residential fires account for only about 1/4th of fire incidents, but are responsible for an overwhelming 3/4ths of the fire-related deaths and injuries. Furthermore, these fires are responsible for the majority of dollar loss due to fires. This data is shown in Figure 1 below.

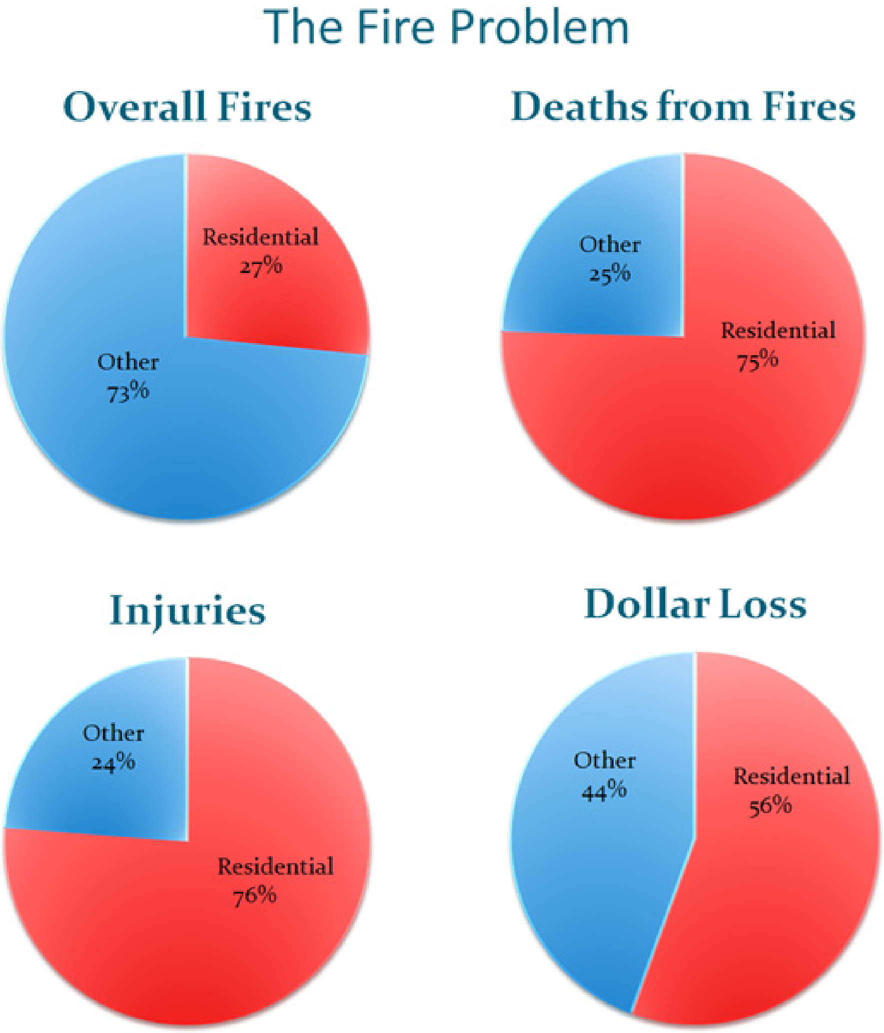


Figure 1. The Fire Problem.
Source: Fire and Fire Losses, from *Fire in the United States 2003-2007* by the U.S. Fire Administration. (p. 49)

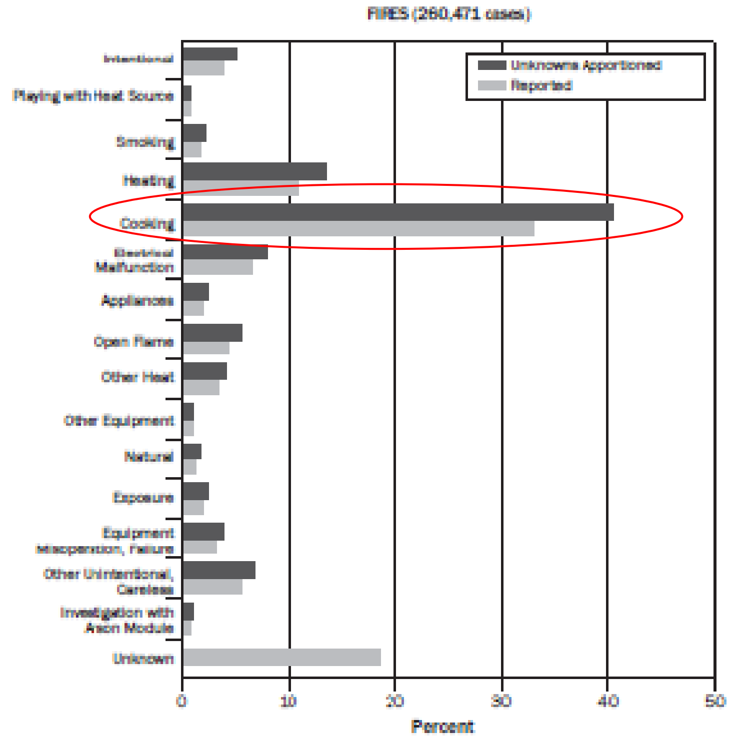
The above data was analyzed from the U.S. Fire Administration's report encompassing data from the National Fire Incident Reporting System and the National Fire Protection Association from 2003-2007. Residential fires included dwellings, duplexes, manufactured homes, apartments, townhouses, rowhouses and condominiums. The majority of the residential deaths occurred in one and two-family properties (USFA 3) The category labeled “other” includes commercial or non-residential properties, vehicles, outside fires, and other miscellaneous fires.

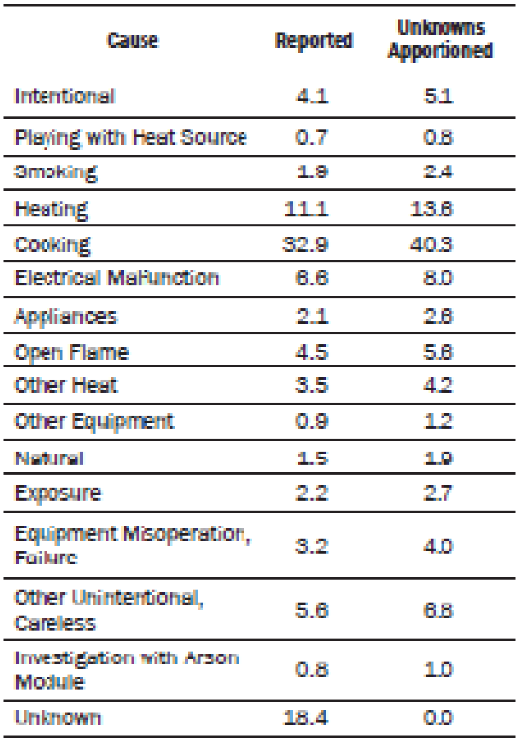
This problem affects individuals and families on a personal level when their loved ones are injured and they lose money and property. The causes of these fires should be investigated so that a solution can be innovated to reduce the amount of residential fires that burn out of control, causing injuries, deaths, and monetary loss.

Residential Fires

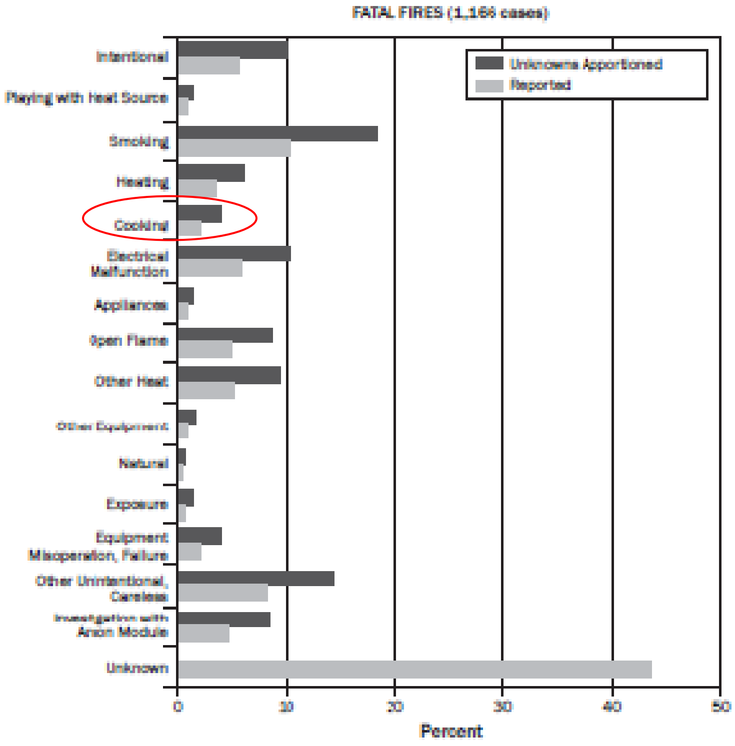
Cooking fires contribute to a significant proportion of residential fires. Overall, cooking is the leading cause of residential fires, at 40%. Other causes vary, and include heating at 14%. Out of the fires that caused injuries, cooking is also a leading cause at 26%. Furthermore, cooking is also the leading cause of fires resulting in property loss, accounting for 20%. The only category that cooking was not a leading cause was in fatal fires. Out of residential fires resulting in deaths, the two leading causes are smoking, at 18%, and unintentional or careless actions, at 14%. (USFA 3) Figure 2 shows graphs from the U.S. Fire Report that compare the different causes of residential fires. On the charts, the light grey line is the actual reported statistic, while the darker gray is the apportioned amount, which estimates to include all the non-reported fire cases.

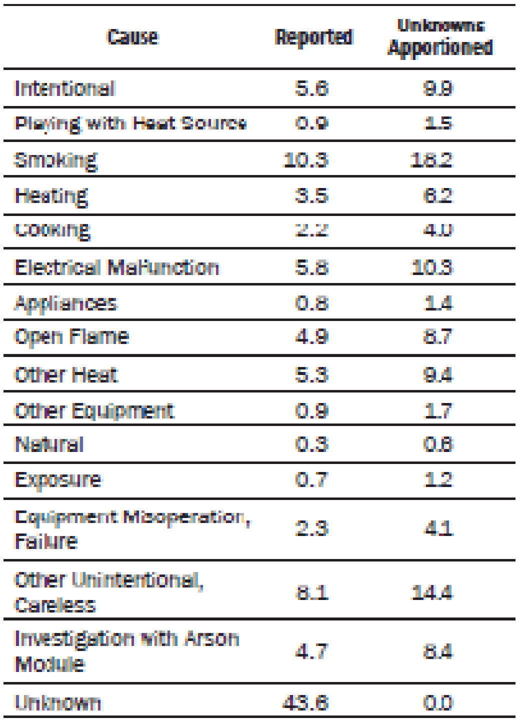
Figure 21. Causes of Residential Structure Fires and Fire Losses (2007)





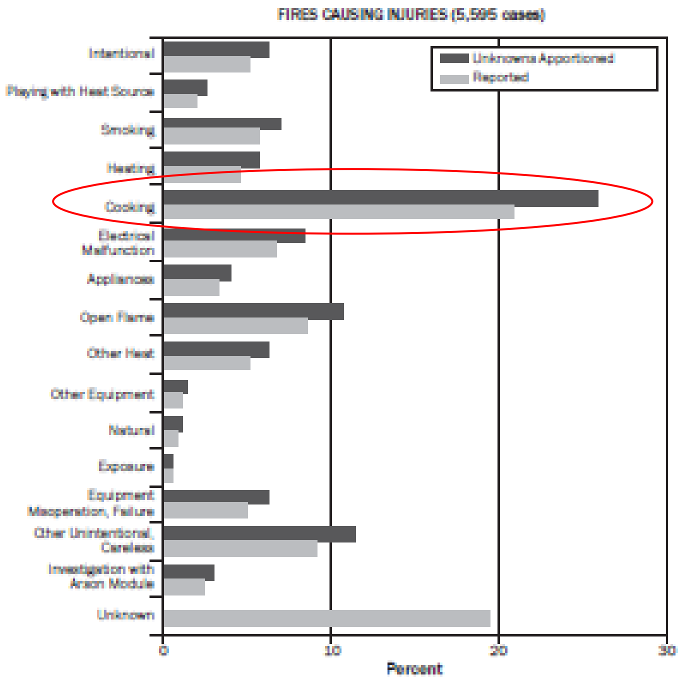
Cause	Reported	Unknowns Apportioned
Intentional	4.1	5.1
Playing with Heat Source	0.7	0.8
Smoking	1.9	2.4
Heating	11.1	13.8
Cooking	32.9	40.3
Electrical Malfunction	6.6	8.0
Appliances	2.1	2.8
Open Flame	4.5	5.8
Other Heat	3.5	4.2
Other Equipment	0.9	1.2
Natural	1.5	1.9
Exposure	2.2	2.7
Equipment Misoperation, Failure	3.2	4.0
Other Unintentional, Careless	5.6	6.8
Investigation with Arson Module	0.8	1.0
Unknown	18.4	0.0



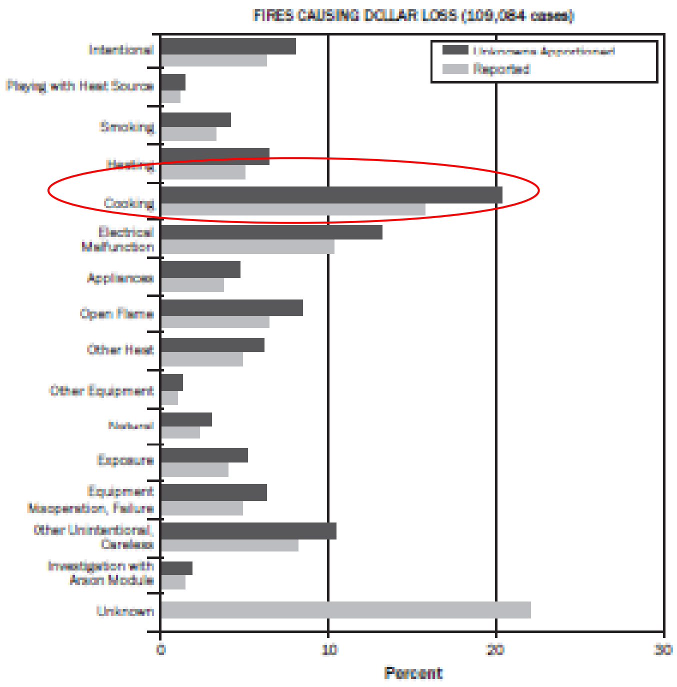


Cause	Reported	Unknowns Apportioned
Intentional	5.6	9.9
Playing with Heat Source	0.9	1.5
Smoking	10.3	18.2
Heating	3.5	6.2
Cooking	2.2	4.0
Electrical Malfunction	5.8	10.3
Appliances	0.8	1.4
Open Flame	4.9	8.7
Other Heat	5.3	9.4
Other Equipment	0.9	1.7
Natural	0.3	0.6
Exposure	0.7	1.2
Equipment Misoperation, Failure	2.3	4.1
Other Unintentional, Careless	8.1	14.4
Investigation with Arson Module	4.7	8.4
Unknown	43.6	0.0

Figure 21. Causes of Residential Structure Fires and Fire Losses (2007)—Continued



Cause	Reported	Unknowns Apportioned
Intentional	5.1	6.3
Playing with Heat Source	2.0	2.5
Smoking	5.6	7.0
Heating	4.5	5.6
Cooking	20.9	25.9
Electrical Malfunction	6.6	8.3
Appliances	3.2	4.0
Open Flame	8.5	10.6
Other Heat	5.1	6.3
Other Equipment	1.1	1.4
Natural	0.9	1.1
Exposure	0.5	0.6
Equipment Misoperation, Failure	5.0	6.2
Other Unintentional, Careless	9.1	11.3
Investigation with Arson Module	2.4	3.0
Unknown	19.5	0.0



Cause	Reported	Unknowns Apportioned
Intentional	6.3	8.0
Playing with Heat Source	1.1	1.4
Smoking	3.2	4.1
Heating	5.0	6.4
Cooking	15.8	20.3
Electrical Malfunction	10.2	13.1
Appliances	3.6	4.6
Open Flame	6.4	8.3
Other Heat	4.8	6.1
Other Equipment	0.9	1.2
Natural	2.2	2.9
Exposure	4.0	5.1
Equipment Misoperation, Failure	4.8	6.2
Other Unintentional, Careless	8.1	10.4
Investigation with Arson Module	1.4	1.8
Unknown	22.0	0.0

Figure 2. Causes of Residential Fires.
Source: Fire and Fire Losses, from *Fire in the United States 2003-2007* by the U.S. Fire Administration. (p. 52-3)

Cooking Fires

Cooking fires are an important type of fire to study because they contribute to a significant proportion of residential fires, resulting in injury and property loss. By identifying and understanding the causes behind cooking fires, steps could be taken to either prevent ignition, or act quickly before the fire becomes out of control. There are several ways in which fires originate in the kitchen.

The equipment that is involved in ignition is important. According to NFPA's analysis of data from 2003 to 2006, ranges and stovetops were by far the leading equipment that was involved in ignition of cooking fires. This is shown in Figure 3.

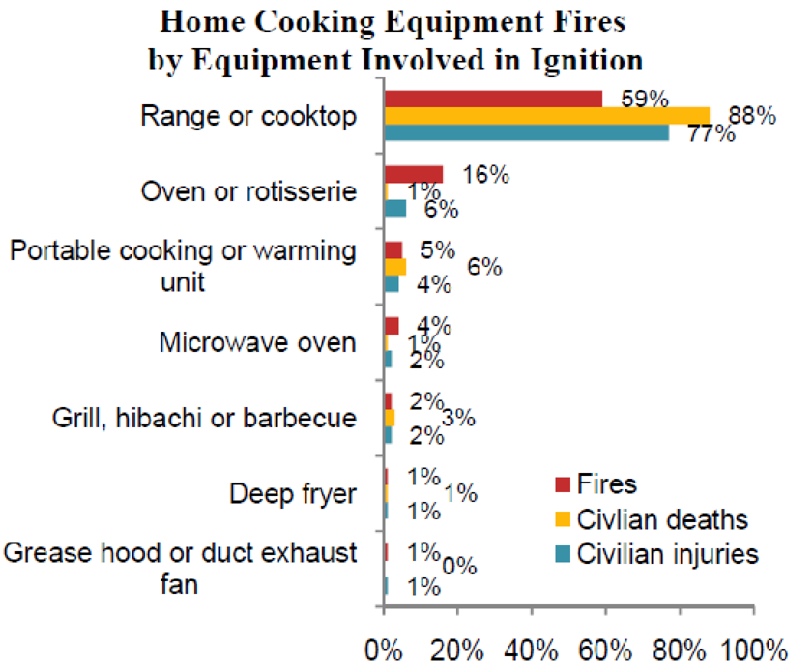


Figure 3. Percentages of cooking fires by equipment involved.
Source: Home Fires Involving Cooking Equipment, *NFPA*.

Human error also plays a large role in the ignition of cooking fires. The leading causes of cooking fires were the cooking equipment was left unattended at 38%, the heat source was too close to combustibles at 12%, and the stove was unintentionally turned on or not turned off, at 10%, and abandoned or discarded material or product, at 8%. (Ahrens)

A majority of cooking fires began with the ignition of food or cooking materials. The Consumer Products Safety Commission (CPSC) conducted a study of reported cooking fire incidents from October 1994 to July 1995. They investigated 289 cooking fires reported by the fire service during that time. Food ignitions accounted for 75% of the incidents, and most among these were rangetop (88%), as opposed to oven fires. Of the total food ignition fires, 93% began with the ignition of cooking oil. Often the oil was overheated and ignited in the pan before the food was even added. (CPSC 32) Therefore, cooking oil is a major factor to study within the topic of cooking fires, in the broad spectrum of residential fires.

Electric vs. Gas Stoves

Of the two most common types of stoves, electric stoves appear to be more dangerous than open flame gas stoves. This may seem counterintuitive because an open flame seems more dangerous than a hot metal coil. But the reasons for the higher danger apparent with electric stoves include several key differences. With gas stoves, people are more aware that the stove is on because of the visual flame and sound, as opposed to the subtle glowing of an electric stove. The cook also has more control over the heat output, and the residual heat on the stove burner dissipates more quickly than on an electric burner after it is switched off. The flame size can also be adjusted to the size of the pan, rather than a set burner size of an electric coil. But in both scenarios, danger can occur when the stove is initially set on high to heat the oil, and then left unattended. (Wijayasinghe & Makey)

Ignition of Cooking Oil

The ignition of cooking oil accounts for almost 3/4ths of cooking fires, while cooking fires are the leading cause of residential fires. If a cooking fire is ignited when a person is not directly around or awake, the fire can quickly grow out of control. Most homes do not have sprinklers to quickly suppress a fire. Cooking oil fires are particularly dangerous because the burning oil produces different properties than in typical fires.

In its Own Class

Cooking oil is categorized by NFPA 321 as a class III combustible. Pertaining to fire extinguishers, cooking oil fires are defined as Class K by the National Fire Protection Organization (NFPA) because they exhibit such different behavior from other liquid fuel fires. They are difficult to extinguish and easy to ignite. When the oil ignites, the auto-ignition temperature can also become lower. Consequently, after the fire is initially put out, it can easily re-ignite if the oil is not cooled below the new auto-ignition temperature. (Voelkert) Class K wet chemical fire extinguishers are relatively new, and discharge a fine mist of a potassium acetate based, low PH agent that also cools the fire. It helps to prevent grease splash and fire re-ignition by cooling. (BFPE)

Auto-Ignition of Cooking Oil

It would be very beneficial to study the various factors surrounding the ignition of cooking oil. The size of the pan, amount of cooking oil in the pan, the amount of heat flux incident on the pan would all affect the time to auto-ignition of the oil. Also, the properties of the oil would determine the auto-ignition temperature of the oil. More refined oils tend to have higher smoke points than less refined oils.(Good Eats) This could give an assumption that correlates to higher auto-ignition temperatures in more refined oils due to different chemical compositions. Therefore different types of oil would have different auto-ignition temperatures, resulting in different ignition times. The results could give insight into safer oils to use that have higher auto-ignition temperatures.

Past Experiments

Canola Oil Auto-Ignition

Several experiments have documented the auto-ignition temperature for canola oil. The documented auto-ignition temperature for canola oil ranges from 330-360 °C. (Przybylski) Literature from an experiment analyzing canola oil fire characteristics and extinguishment had ranges of auto-ignition temperatures from 351-361 degrees Celsius. (Liu) Also, in a UL 300 test, an unspecified shortening auto-ignited at 363 deg C. (Voelkert) Based on these temperatures, an experiment was designed and conducted in which the auto-ignition temperature was reached using a mini pan and hot plate.

NIST, UL300A Extinguishing Test

Experiments were conducted at the National Institute of Science and Technology that characterized kitchen oil fires using UL 300A*, Extinguishing System Units For Residential Range Top Cooking Surfaces,* to test different extinguishing methods for fires occurring on range top kitchen surfaces. This test was primarily to study the flame after ignition and test extinguishing methods. But it gives some information on what to expect for time to ignition for normal to large scale cooking oil fires.

There were 14 test scenarios, which used four different types of pans of different sizes and materials (cast iron and stainless steel), with different amounts of vegetable and peanut oil (ranging from depths of ¼", 1" and 4"). Both electric and gas stoves were used in the tests. Measurements were taken to determine the ignition time, flame height, heat release rate, heat flux (both vertical and horizontal) and the temperatures at the bottom, middle and top of the pan.

The shortest time to ignition was 18 minutes, but the fire quickly reached its peak heat release rate within 1-2 minutes. Figure 4 shows the stages of the fire, from ignition to 3 minutes into burning. The heat release rate is plotted against time, and the fire reached the peak heat release rate about 50 seconds after ignition, and then tapered off. (Madrzykowski)

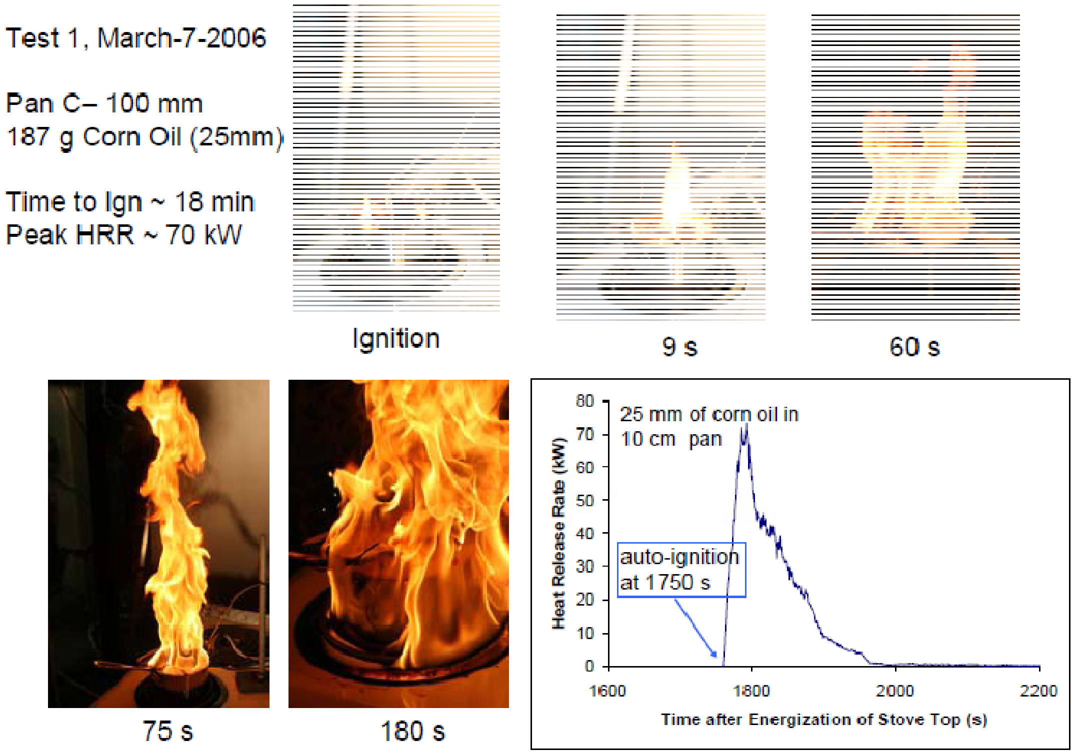
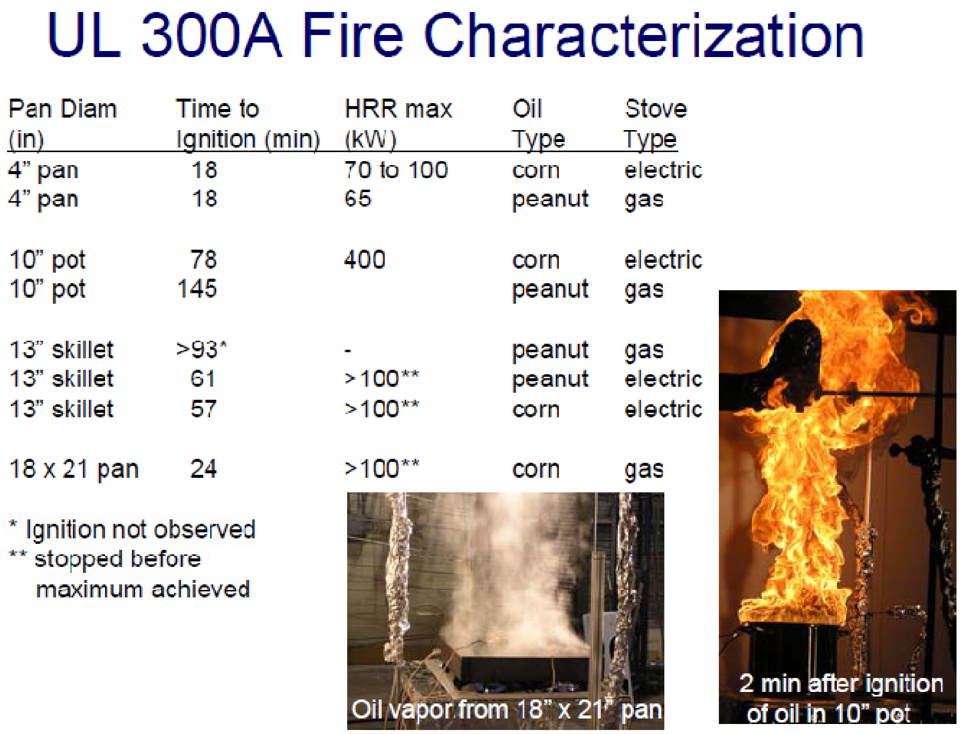


Figure 4. Data from one UL 300A test.
Source: Daniel Madrzykowski, NIST Special Publication 1066; Appendix 6.



UL 300A Fire Characterization

Pan Diam (in)	Time to Ignition (min)	HRR max (kW)	Oil Type	Stove Type
4" pan	18	70 to 100	corn	electric
4" pan	18	65	peanut	gas
10" pot	78	400	corn	electric
10" pot	145		peanut	gas
13" skillet	>93*	-	peanut	gas
13" skillet	61	>100**	peanut	electric
13" skillet	57	>100**	corn	electric
18 x 21 pan	24	>100**	corn	gas

* Ignition not observed
** stopped before maximum achieved

Oil vapor from 18" x 21" pan

2 min after ignition of oil in 10" pot

Figure 5. UL 300A Fire Characterization.
Source: Daniel Madrzykowski, NIST Special Publication 1066; Appendix 6.

From the data summarized in Figure 5, it appears that the oil heated on electric stoves auto-ignited more quickly than on gas stoves. The maximum heat release rate was also higher for the electric stove. This corresponds with the reasoning as to why electric stoves are more dangerous than gas stoves.

Auto-Ignition and Extinguishment by Water Mist

An experiment was conducted by people from the National Research Council of Canada which gives insight into some properties of canola oil fires. "Characteristics of large cooking oil pool fires and their extinguishment by water mist" heated up canola oil in a pan, let it auto-ignite, and then analyzed the fire and extinguishing by water mist. Water mist is an effective extinguishing method because it cools the fire, yet does not cause the large amount of spatter that results from ordinary sprinklers. From a total of seven experiments, the auto-ignition temperatures of canola oil ranged from 351-361 degrees C. (Liu) The smoke/oil vapor began appearing over the oil surface when the oil was heated to 220 degrees C.

Auto-Ignition Temperatures Experiment

An experiment was designed and several tests were conducted to determine the auto-ignition temperatures of cooking oils. A small amount (5 mL) of cooking oil was heated in a small pan on a hot plate until the oil auto-ignited. The hot plate was set to a constant heat flux to simulate an electric stove. A thermocouple measured the temperature of the oil in the pan. The thermocouple was also connected to a data acquisition system that recorded the temperature each second. All temperatures are in degrees Celsius.

Three fairly common household cooking oils were tested. Canola oil was tested first because the auto-ignition temperature was expected to be between 330-360 degrees C. Next, vegetable (soybean) oil and extra virgin olive oil were tested. Then Smart Balance (margarine) and butter were tested using a slightly modified procedure.

Types of Oils

Liquid

1. Canola Oil: “Trader Joe’s 100% canola oil, expeller pressed, no solvents used. Mechanically extracted with no solvents, chemicals or additives.” Made in Canada

2. Soybean Oil: “Pure Wesson 100% Natural Vegetable Oil,” Ingredient: Soybean Oil. Con Agra Foods, Nebraska, USA.

3. Olive Oil: “Rienzi extra virgin olive oil,” obtained “directly from olives, solely by mechanical means.” Imported from Italy.

Solid

1. Margarine: “Smart Balance buttery spread” original. Ingredients: Natural oil blend (soybean, palm fruit, canola and olive oils), water, contains less than 2% of salt, whey, etc.

2. Butter: ordinary table butter. (Fat content from www.nutritiondata.com for butter, salted)

	Total Fat	Saturated	Polyunsaturated	Monounsaturated
Canola Oil	4.67	.33	1.33	2.67
Soybean Oil	4.67	.67	2.67	1
Olive Oil	4.67	.67	.67	3.33
Smart Balance	3	.83	1.17	1
Butter	2.43	1.55	.09	.63

Table 1. Types of fat in each oil used. Values are in grams per 5 mL.

Temperature of the Hot Plate

The temperature of the hot plate at the maximum setting was estimated to be around 500-530 degrees C. This was estimated by keeping the thermocouple in contact with the hot plate by pressing down on the end using a pan. The heat could have been lost or dissipated without the pan on top, but with the pan on top, the heat may also have been trapped by the pan, giving a higher temperature reading. For reference, the hot plate used was a Thermolyne Cimarec 2.

Experimental Procedure

Materials

- Hot plate
- Thermocouple
- Small pan, 3.57 cm diameter (aluminum tea light holders were used)
- Measuring beaker for 5 mL
- Canola Oil, Soybean Oil, Olive Oil, Margarine and Butter
- Data acquisition system (if available)
- Safety Goggles

Precautions

Throughout the experiment, it is important to consider safety. Safety glasses should be worn to protect your eyes from any possible oil spatter when the oil ignites and burns. Also, the workspace should be clear of combustibles that are not involved in the experiment. The surfaces surrounding the hot plate should also be wiped down of oil between experiments so that any stray oil does not ignite.

Preparation

First the aluminum tea light holders, which will be called pans from now on for simplicity, are cleaned and allowed to dry completely. Each test will use a new pan. Then 5 mL of oil at room temperature is measured out in a beaker and then poured into the pan. The oil should be about 4 mm deep, and should be measured out within 5 minutes of the start of the test to help each test produce consistent results. For solid fats, 1 teaspoon was measured, which is equivalent to 5 mL. The margarine/butter should be allowed to sit at room temperature for 1-2 hours prior to the experiment to adjust to the ambient temperature.

Position the hot plate under the ventilation hood, and place the pan of oil on the hot plate. To minimize any possible variations in the experiment, the pan should be put on the same spot on the hot plate each time. Prepare the thermocouple, positioning it so that the tip of the thermocouple is 1-2 mm below the surface of the oil, in the center of the pan. To get an accurate, repeatable reading, make sure that it is not touching the bottom of the pan. The thermocouple tip should be 1-2 mm below the surface of the oil. Throughout the test, it should be monitored to ensure that the thermocouple is still submerged, but not touching the bottom. A photo of the test setup is provided in Figure 6. If you are using a data acquisition system, prepare the system so that it is ready to begin collect data. Turn the ventilation system on when you are ready to begin.

Procedure

Auto-Ignition Tests

Turn the hot plate on to the highest setting and begin the data acquisition system. Observe the behavior of the oil as it heats up, recording the first temperature at which smoke is first observed, boiling begins, and auto-ignition occurs. When the oil ignites, allow it to burn freely until it self-extinguishes when all the fuel is burned up. Then turn the data acquisition system off, turn the hot plate off and remove the thermocouple. Allow the pan to cool completely before removing it from the hot plate, or use tongs or an insulated glove to move the pan. Let the ventilation system run for another five minutes to clear up the smoke.

Solid Fat Tests

The procedure was slightly different for the fats that were solids at room temperature. During preparation, the butter or margarine was allowed to sit at ambient temperature for an hour to soften, and was then placed on the warm hot plate and allowed to melt at the lowest hot plate setting. When the butter/margarine was completely melted and the temperature was between 60 to 90 degrees, the heat was turned up to the highest setting and the test was continued in the same manner as the liquid oil tests. A good idea for future solid fat tests would be to turn the heat to maximum as soon as the butter/margarine is completely melted. That would produce greater repeatability and likely less variation among the results.

Flame Point Tests

Prepare the set-up as described in the preparation. Turn on the hot plate to the highest setting. When smoke is observed coming off the oil, record the smoke point and lower the setting on the hot plate so that the temperature increases by about 1 degree every second. Record the temperature at which the oil begins to boil. After boiling begins, wave a flame over the surface of the oil every 3 to 5 seconds. Record the temperature at which the oil ignites.

Clean Up

After each experiment, wipe down the area around the hot plate and make sure there are no pools of spatters of oil nearby the hot plate.

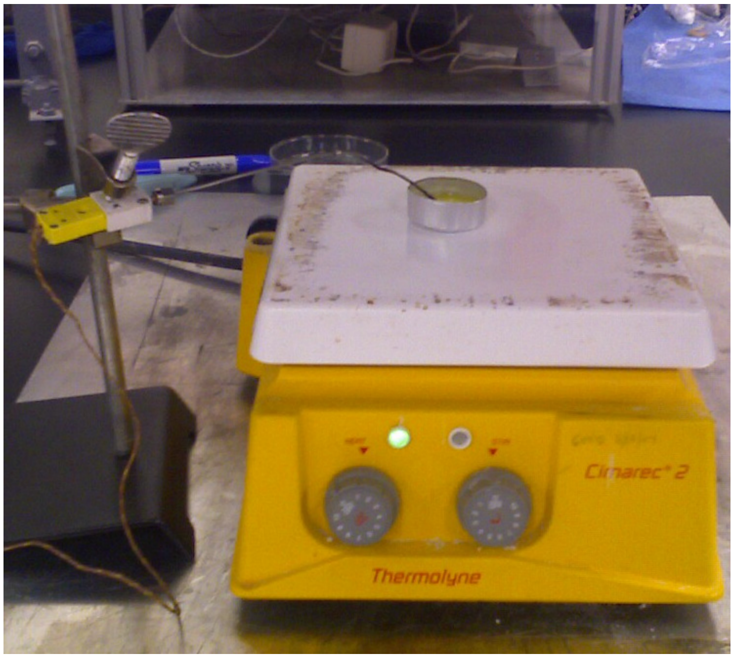


Figure 6. Test setup.

Results: Auto-Ignition Temperatures

For each oil tested, the auto-ignition temperatures were in the same range. A total of 5 experiments were done with canola oil, 3 with soybean oil, 3 with olive oil, 2 with Smart Balance and 2 with butter. The average auto-ignition temperatures for each oil are provided in Table 2 below.

	Canola Oil	Soybean Oil	Olive Oil	Smart Balance	Butter
Auto-ignition temperature (℃)	424	406	435.5	423	Did not ignite

Table 2. Auto-Ignition temperatures of oils tested.

Observations

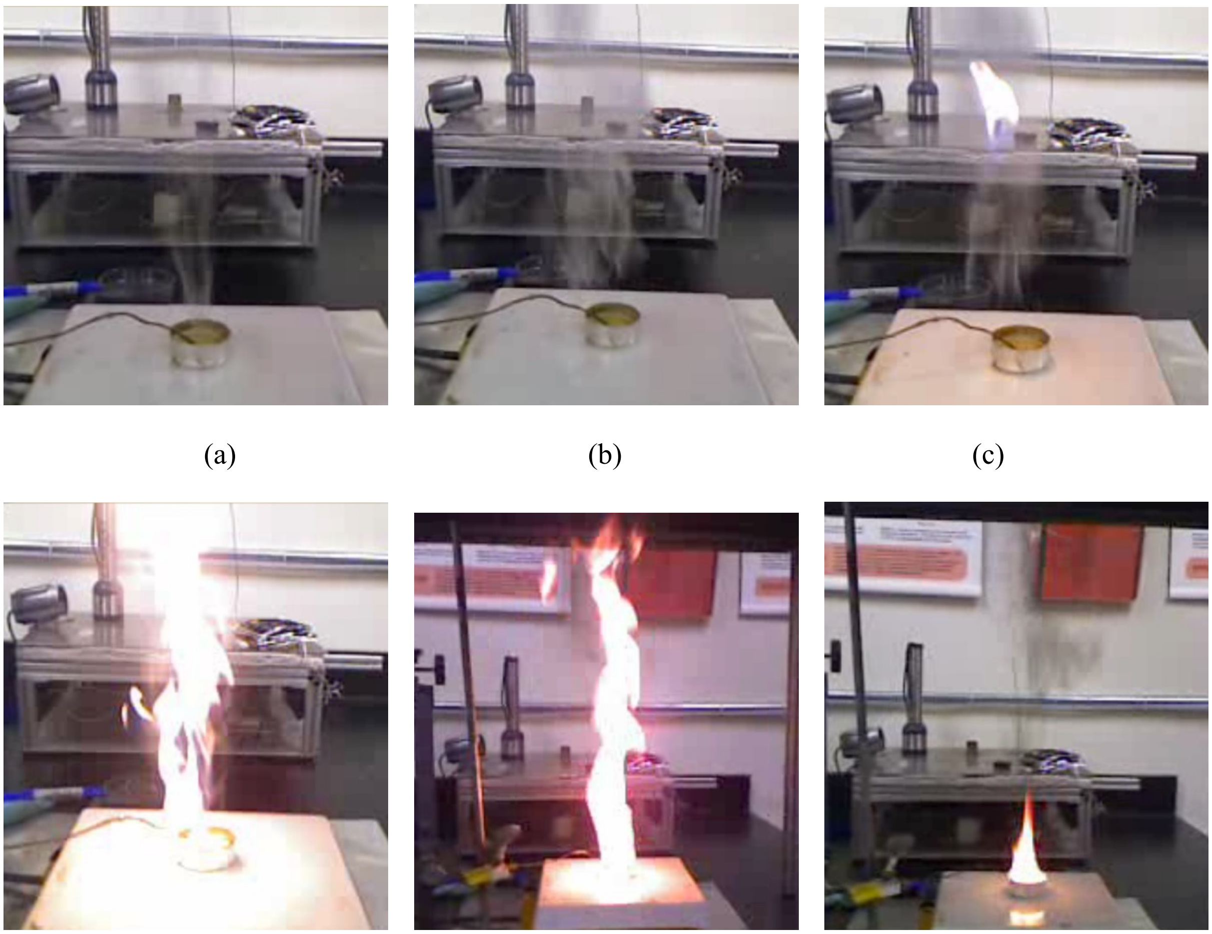
Canola Oil

As the oil heated up, it began to pyrolize and produce very light smoke at the lowest observed temperature of 154 degrees. This smoke was barely visible. As the temperature increased, the smoke became more visible around 269-275 degrees. Around 300 degrees, the smoke began to leave yellowish residue around the inside of the pan, above the oil level. This residue became darker and piled up more as the temperature and smoke increased.

The first observation of light boiling began at 355 degrees. The oil became noticeably yellower at 405 degrees, and the smoke became thicker. The boiling increased to a rapid boil, and the surface of the oil began frothing between 420-425 degrees, shown below in Figure 1(a) from experiment 4. Smoke was now thicker and grey, and was being produced at a faster rate. At this point, the oil was almost ready to auto-ignite as seen in Figure 1(b). The oil auto-ignited at 433 degrees in this particular test, as shown in Figure 1(c). The full auto-ignition is shown in Figure 1(d). Neglecting the outlier, the auto-ignition temperatures were between 427 and 433, with 433 being the mode, or most frequent occurrence, occurring twice out of five trials.

After ignition, the flame initially was initially 2-3 inches high for experiment 5, where the hot plate was initially considerably cooler than experiments 3 and 4. After about 5 seconds, this flame grew much larger, and burned about 1-2 feet high for about a minute. But in experiments 3 and 4, the flame was rather large initially. The flame was very turbulent and produced black smoke, as seen in Figure 1(e). It was allowed to burn until all the oil was burned up and the flame self-extinguished. The decay is shown in Figure 1(f).

The pan after the test is shown below in Figure 2. The black soot can be seen around the inside edges of the pan.



(a) (b) (c)

(d) (e) (f)

Figure 7. Experiment 4 at various temperatures.
a) 422°C, frothing begins; b) 433°C, immediately before ignition; c) 433°C, at ignition; d) 433°C, full ignition; e) fully developed flame; f)decay 47 sec after ignition

(a) (b)

Figure 8. Pan after experiment.
a) top view at an angle; b) side view at an angle.

From 5 tests using canola oil, the auto-ignition temperatures observed were 431, 433, 398, 433 and 427 degrees Celsius. The 398 value from was probably due to the sampling error of the temperature and response time of the thermocouple. In experiment 3, the outlier, the temperature observed at ignition was 398, and then jumped up immediately later. The thermocouple may have needed a second to respond to the temperature increase at ignition.

The observed auto-ignition temperatures of canola oil are provided in Table 1 below.

Experiment	1	2	3	4	5
Auto-Ignition (°C)	431	433	398	433	427
Time to Auto-Ignition (sec)	Not observed	500	345	360	476

Table 3. Auto-ignition data for canola oil.

Soybean Oil

The soybean oil exhibited characteristics similar to canola oil as it heated up. Smoke was first observed at the lowest temperature of 146 degrees. By 350 degrees, the smoke was more visible and yellow residue was beginning to build up on the inside rim of the pan, above the oil level. It began to boil around 355 degrees, and the intensity increased. By 390 degrees, the bubbling was rapid, lots of smoke was being emitted, and the oil began turning a yellow color. The smoke and bubbling became more intense leading up to the auto-ignition. The auto-ignition temperatures observed for soybean oil are provided in Table 4 below.

Experiment	1	2	3
Auto-Ignition (°C)	411	405	403

Table 4. Auto-ignition data for soybean oil.

Olive Oil

The characteristics of the oil as it heated up, began to smoke and boil were very consistent among the three experiments using olive oil. The only exception was that the 2nd test did not auto-ignite.

Smoke was just barely visible at 130 degrees, and boiling first began at 350 degrees. The smoke began coming up faster once boiling began, and as the boiling increased to a rapid boil, the smoke emission increased. Around 400 degrees, the oil began frothing at the edges from the bubbles. At 435-439, the temperature lingered as the oil continued to rapidly boil. In the experiments 1 and 3, this was the point at which the oil auto-ignited.

In test 1, the temperature lingered around 433 degrees for about 10 seconds before increasing to 437 and auto-igniting. In test 3, the oil auto-ignited at 434 degrees. But in the 2nd experiment, the oil instead began turning a dark yellow-brown color. The temperature very slowly increased up to 448, and then started slowly going back down to around 439. The oil was evaporating and less and less was left in the pan. At 356 degrees, the temperature began decreasing even more, and by 310 degrees all the oil was gone. In the second test when the oil did not ignite, it left behind different characteristics. A strong burning smell was released and there was a layer of black residue around the bottom of the pan, as seen in Figure 9 below.

The auto-ignition data for olive oil is provided in Table 5 below.

Experiment	1	2	3
Auto-Ignition (°C)	437	Did not ignite	434

Table 5. Auto-ignition data for olive oil.

Figure 9. Olive oil pan after no ignition occurred.

Discussion

Time vs. Temperature, Canola Oil

Test 1 was only observed and was not recorded with the data acquisition system. The subsequent tests using canola oil were recorded and plotted in a temperature-time graph shown below in Figure 8.

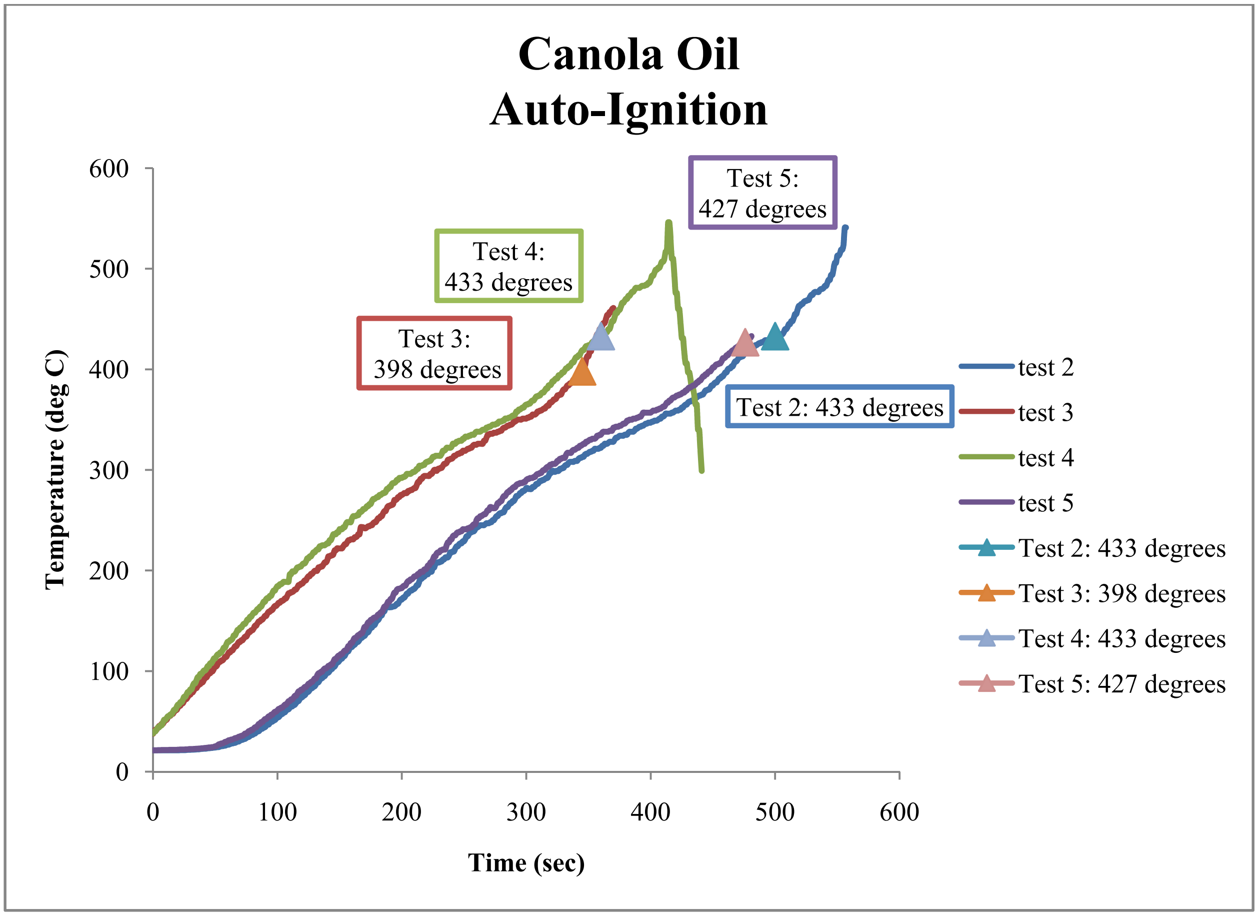


Figure 10. Canola oil: temperature vs. time and auto-ignition temperatures.

Temperature Rate of Increase, Canola Oil

Both tests 1 and 2 began with a completely cooled hot plate. These tests resulted in auto-ignition temperatures within 2 degrees. Test 5 began after the hot plate was cooled for about 10 minutes, which brought the surface temperature of the hot plate down considerably, although not completely to room temperature. Consequently, as shown in Figure 8, the temperature versus time plot of experiment 5 was extremely similar to experiment 2. The oil heated up gradually at first because the hot plate needed to heat up, resulting in a longer time to reach ignition temperature than in tests 3 and 4. Of tests 2 and 5, the average time to auto-ignition was 488 seconds.

Between tests 2 and 3, the hot plate was kept on an additional 5-10 minutes while the hot plate temperature was evaluated. The hot plate was allowed to cool for about 5 minutes after this, before experiment 3 began. The hot plate was turned off following burnout of experiment 3, and was allowed to sit and cool for about 5 minutes before experiment 4.

Both experiments 3 and 4 began while the hot plate was still considerably hot. With the initial plate temperature higher than ambient conditions, the initial temperature increase is more linear than when starting with a completely cooled plate, as seen in Figure 8. For these two tests, the oil reached auto-ignition temperature more quickly than in tests 2 and 5. For tests 3 and 4, the average time to auto-ignition was 352.5 seconds.

The slope of temperature increase after the oil reaches about 50 degrees is very similar among the experiments. This is due to the consistency of parameters in the experiment and the constant heat flux from the hot plate.

To get repeatable results for a temperature vs. time curve, either the plate should be cooled completely between tests, or it should be cooled for the same amount of time between tests. A good idea is to shut the hot plate off for five minutes between tests. An alternative would be to leave the hot plate on, but this would require a very quick set-up of placing the pan on the hot plate, positioning the thermocouple correctly, and beginning the data acquisition system simultaneously.

Points of Interest, Liquid Oils

With a constant heat flux applied throughout the experiment, the temperature increase with time for the liquid oil tests can be compared among results in Figures 9 thru 11 below.

The rate of temperature increase begins to increase linearly until the oil reaches its smoke point. After the smoke point, the rate of temperature increase is slowly decreasing as the curve becomes concave. When the boiling point is reached, the rate of temperature increase becomes quicker. This can be seen on the graphs below, where the boiling point appears coincide with the point at which the slope changes and the curve becomes convex. The rate continues to increase until the auto-ignition temperature is reached.

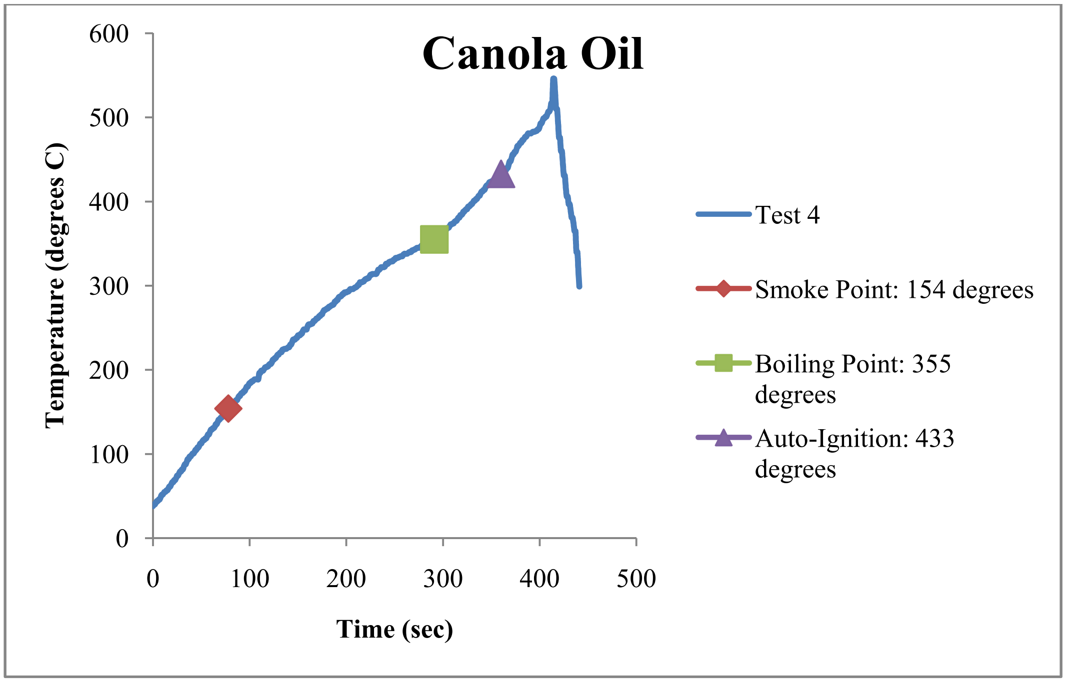


Figure 11. Canola oil (test 4).

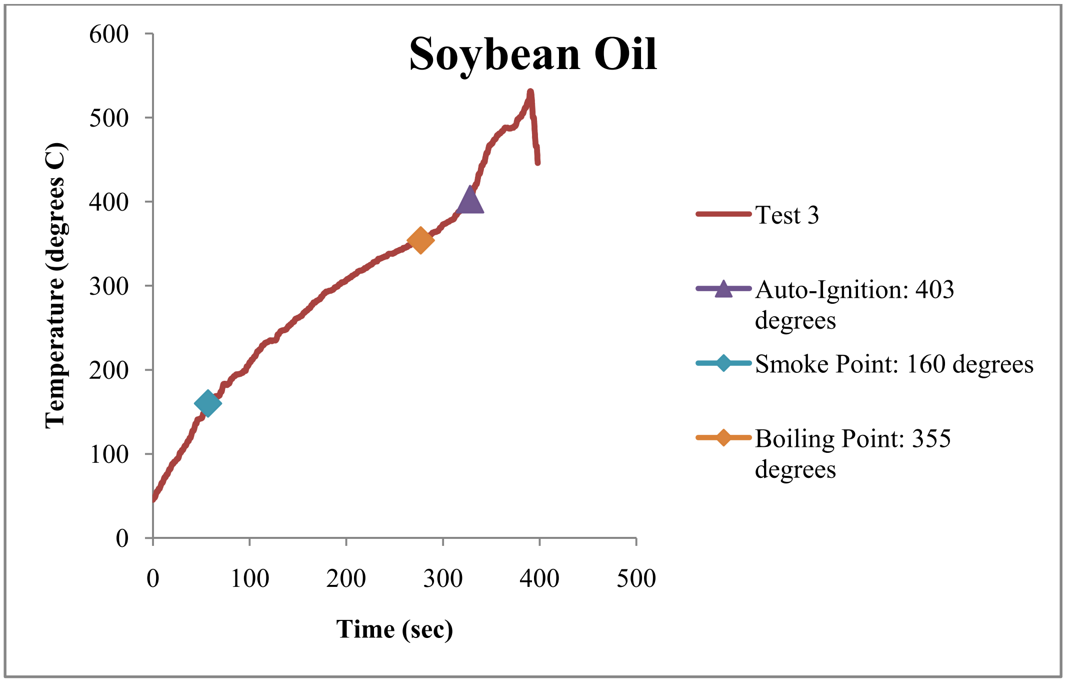


Figure 12. Soybean oil (test 3)

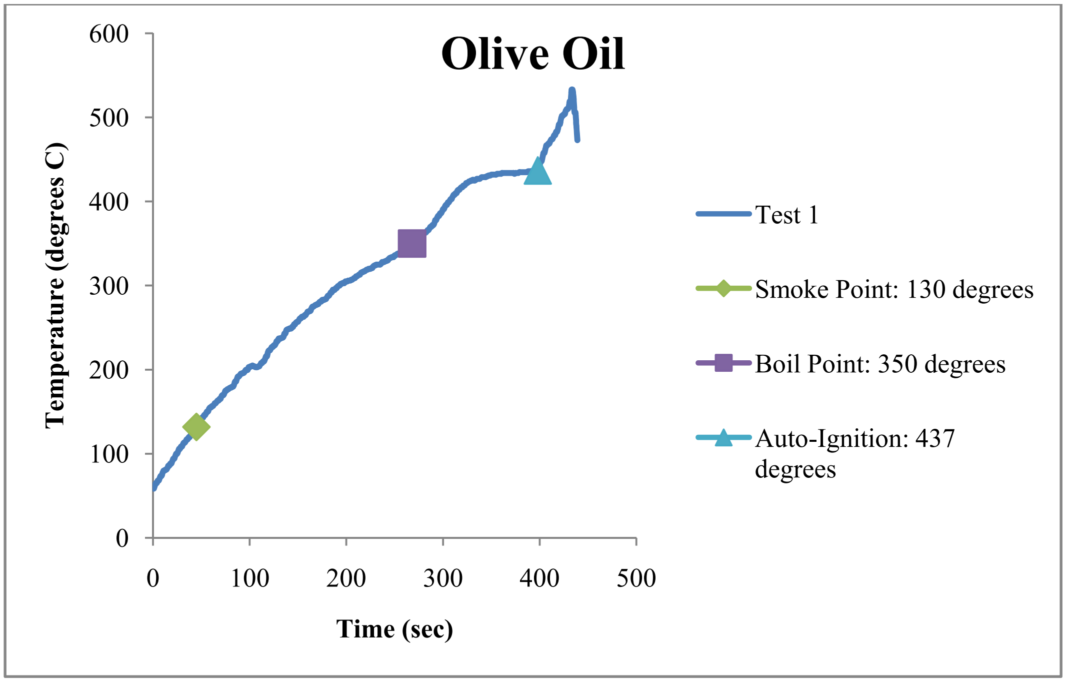


Figure 13. Olive oil (test 1).

A summary of the smoke point, boiling point, and auto-ignition temperatures for each liquid oil is provided below in Table 6. The average auto-ignition point of canola oil below neglects the outlier, which was 398 degrees. The smoke point varied among the 3 oils, but all 3 oils began to boil around the same temperature. After boiling begins, the temperature quickly increases as the boiling intensity increases. This is the main indicator that the oil is becoming ready to auto-ignite.

Soybean oil had the lowest average auto-ignition temperature at 406 degrees, and canola and olive oil were similar, auto-igniting at 431 and 435.5 degrees respectively.

	Canola	Soybean	Olive
Smoke Point	154	160	130
Boiling Point	355	355	350
Auto-Ignition Point (avg)	431	406	435.5

Table 6. Points of interest: smoke, boiling, and auto-ignition temperatures (degrees Celsius).

Flame Test

A flame test was conducted and the oil was heated up quickly initially until the oil began emitting smoke. Then the rate of temperature increase was slowed down, to about 1-2 degrees per second. Every 3-5 seconds, a pilot flame was passed directly on top of the surface of the oil. The temperature at which the oil ignited the first time was 385 degrees. The second test, the oil barely caught the flame at 373 degrees, and the flame spread to the entire surface of the oil by 383 degrees. The flame began small, about 2-3 inches, then flared up in 5-10 seconds, burning for about one minute. From these two tests, the average flame point temperature for canola oil was 379 degrees.

Solid Fats

Both the Smart Balance and butter showed very different characteristics from the liquid oils. as they were heated. The smart balance was a breed of its own Unless the ignition temperature range is known, it is very difficult to predict the point at which the smart balance will auto-ignite because the behavior changes back and forth as the temperature increases. The butter, however, did not auto-ignite. Both solid fats left behind much more residue in the pan, compared with the liquid oils.

Smart Balance

Two tests were conducted using Smart Balance. The procedure for the Smart Balance (margarine) was a little different because the margarine was initially solid. It was allowed to sit for a few hours to soften, then was put on the already warm hot plate, on the lowest setting.

The time vs. temperature plot of the two tests are shown in Figure 18. The Smart Balance was completely melted at 50 degrees, and began to bubble in spots at 72 degrees. These bubbles were much larger than the bubbles in the oil tests, and spattered a little in the beginning. At 90 degrees, the heat was turned to high to follow the same procedure as the oil tests from this point on. The temperature then lingered around 93-95 degrees, with the bubble size and rate increasing. Smoke was first observed at 98 degrees.

After the smoke point, the temperature increased more quickly. Although the margarine was bubbling fiercely, it did not leave residue on the edge of the pan yet. At 160 degrees, the bubbling stopped and the margarine began appearing brownish and leaving residue. It kept smoking, and the temperature kept increasing. It turned black around 330 degrees. At 400 degrees, it began smoking a lot again, resumed bubbling, and the temperature increased. At 430 degrees, The margarine was rapidly boiling and frothing at the edges. It auto-ignited at 441 degrees in the first test, and 434 in the second test. It burned for about a minute. The margarine by far left more residue in the pan than the liquid oils did. It was very sticky and ended up being black.

An interesting observation is that the boiling point of Smart Balance is lower than the smoke point, which is reversed for all the liquid oils that were tested. The Smart Balance also reached a higher auto-ignition temperature than the liquid oils, about 10 degrees higher than the canola oil.

Just prior to auto-ignition, the temperature increased more rapidly, accompanied by more smoke and more rapid bubbling. But this happened about 2-4 times during the test using Smart Balance before it actually auto-ignited. Perhaps this could be a result of the added salt in the margarine, causing reactions as the temperature increased. Maybe the main oil ingredient in Smart Balance auto-ignites at this temperature.

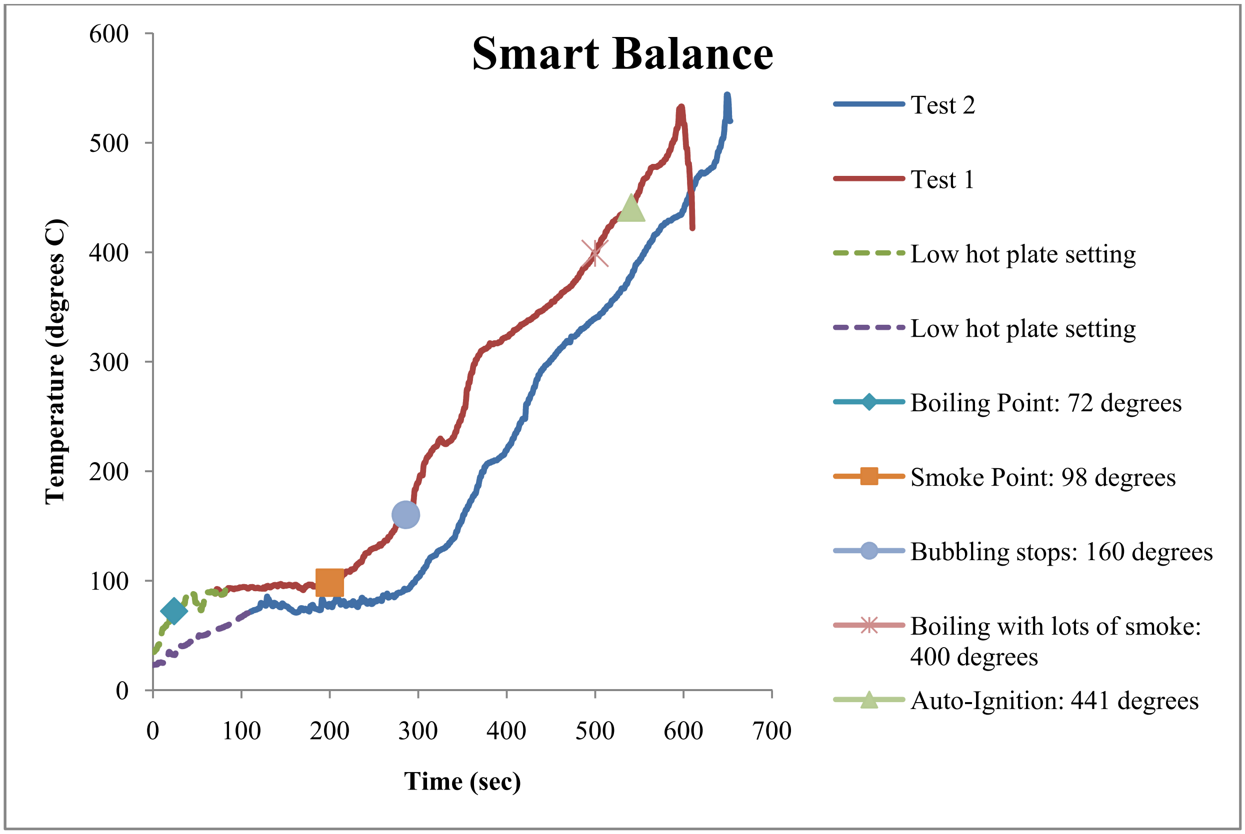


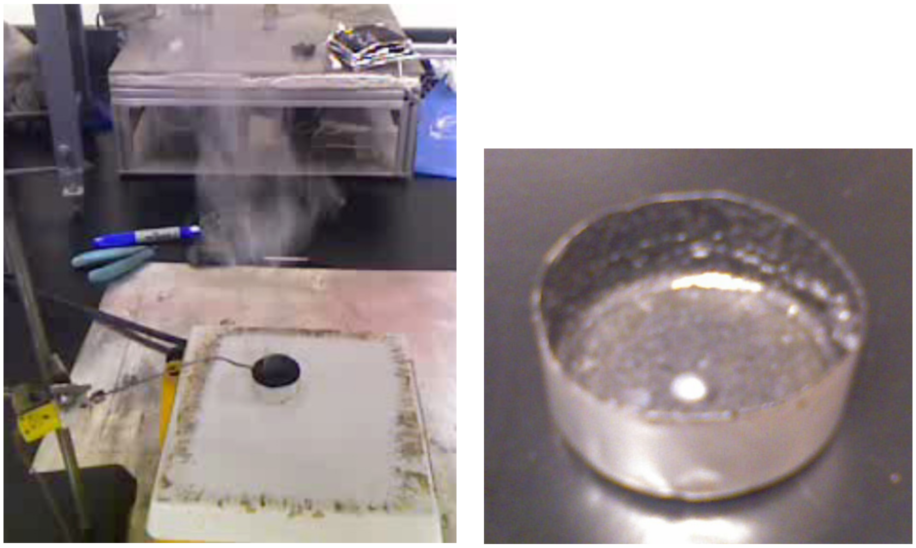
Figure 14. Smart Balance temperature vs. time and points of interest.

Butter

Two tests were conducted using butter, and both did not auto-ignite. These tests left considerably the most black residue in the pan. The butter was initially at room temperature, and placed on the warm hot plate on the lowest setting. It was melted at 35 degrees. At 60 degrees, the hot plate setting was increased to high. A thin white foam appeared over the surface. Key observations on smoke and bubble appearances are noted in the temperature-time plot in Figure 15.

At 85 degrees, the first tiny bubble appeared at the edge, with random tiny bubbles popping up mostly on the outer edge. At 100 degrees, the butter was frothy on top with tiny white bubbles. The bubbles were much smaller than the bubbles observed from the smart balance experiments. At 140 degrees, smoke was first noticed and the bubbles became bigger. At 154 degrees, the bubbles slowed down, the smoke stopped, and the temperature continued to increase. The butter turned more noticeably yellow around 182 degrees.

At 200 degrees, the butter became brown and residue began appearing around the edges. At 220 degrees it began smoking again, and the butter became darker yellowish-brown. At 270, the smoke was rapid and the butter began turning black, and was very black by 300 degrees. At this point, the butter was still 1-2 mm deep, which is about half of what the depth initially was. At 390 the edges began bubbling again and there was lots of smoke. Tiny bubbles began appearing again on the surface at 412 degrees, and it became very smoky by 430 degrees. At 440, it was very black and shallow as shown in Figure 13, and the temperature began to decrease. The smoking stopped completely at 365 degrees, leaving a thick layer of black residue on the bottom and sides of the pan as seen in Figure 14(b) and an extremely strong burning smell.



(a) (b)

Figure 15. Butter: a) at 440 degrees; b)pan after no ignition.

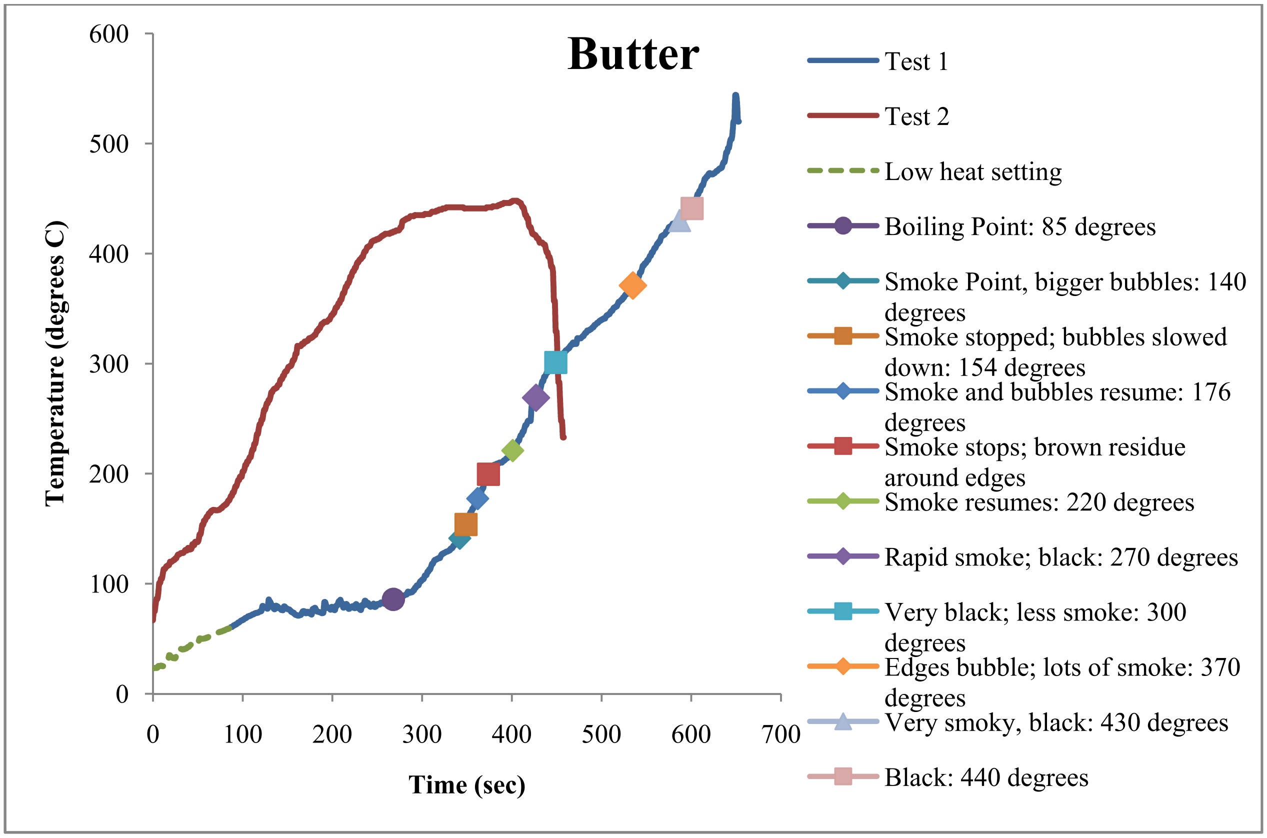


Figure 16. Butter, time vs. temperature and observations.

Conclusion

Time to Ignition

In the tests, the oil was at a depth of 4 mm in the pan, and it auto-ignited in the range of 6-7 minutes. This emphasizes the need to pay close attention while cooking, especially when preheating oil in a pan. As stated earlier, 70% of the cooking fires in the study by the Consumer Products Safety Commission began with the ignition of cooking oil, and most were a result of the oil overheating in the pan before the food was even added. (CPSC) These fires could be avoided if the oil is closely watched while it is heating up. If it is begins to emit smoke, the heat should be lowered because the oil is becoming too hot. If the oil begins to boil, it should be removed from the heat source to prevent auto-ignition before the temperature can become any higher.

The tests beginning with the completely cooled hot plate could be representative of cooking oil fires in which the oil and pan are heated up on an initially cold pan and electric burner. The tests in which the hot plate was initially still hot could represent the instances where cooking is done back-to back on the same burner. This would occur more in restaurants and the food industry, where food is constantly being prepared. Cooks in these situations should be extra attentive while cooking because as seen in the curves, the ignition time is shorter when the heat source is still hot initially.

Ignition Indicators

In the liquid oil tests, the temperature increase slows down after the oil begins to emit smoke and pyrolyze. But once boiling begins, the temperature increases more rapidly as the boiling and smoke emission becomes more intense. When this is observed, the oil is becoming close to its auto-ignition temperature.

The Smart Balance test did not clearly display an indicator before it auto-ignited. It bubbled and smoked intensely a few times as it heated up, and then settled back down. This made it difficult to predict the temperature at which it auto-ignited. The chemical composition of the Smart Balance may have had an effect on this, likely due to the addition of salt and other chemicals. From the nutrition facts, it had 90 mg of salt per 15 mL of Smart Balance.

The butter exhibited behavior similar to Smart Balance, and appeared as if it was ready to ignite at several points during the test. The chemical composition of butter and the possibility of added salt may have had an effect on the reactions as it heated up.

Flame Height

Because the entire volume of oil is at the auto-ignition temperature, the flame is initially very large. For a 5 mL oil fire in a 37.5 mm diameter pan, with an oil depth of 4 mm, the flame flared up to a height of 1-2 feet. It continued to burn for about 1 minute before all the oil was burned up.

In the flame test, where a pilot flame was passed over the oil every few seconds as it heated up, the flame was not as large initially. The pilot flame simulated possible sparks being emitted from metal-on metal contact of a pan with electric heating coils. It could also represent the flame present in gas stoves, which could come close to the oil if the cooking materials are being flipped in the pan, or sautéed. In these tests, the flame was initially 2-4 inches tall for the first 5-10 seconds after ignition. During this time, the cooking fire would be put out relatively easily because of the small flame size. But following this initial flame growth, the rest of the oil heated up and the flame grew to be turbulent and much larger, about 1-2 feet high. The flame could easily spread to other combustibles around the cooking area before all the oil is consumed.

Comparison Among Different Cooking Oils

The butter did not auto-ignite during the test, indicating that it may be a safer alternative to cooking oil. This may be due to the lack of double bonds, polyunsaturated fats, in the chemical composition of butter. Out of all the cooking oils and solid fats tested, the butter had the lowest amount of polyunsaturated fat, .09 g, as shown in Table 1. If butter was being preheated on a stove and accidentally left unattended, it probably would not auto-ignite, making it safer in this aspect. But as it boils, it may be unsafe if the boiling butter spatters. At such high temperatures, the butter would also smoke and pyrolize, leaving behind a significant amount of residue and odor.

The Smart Balance would not be ideal to use for stovetop frying. It auto-ignites at 423 °C, which is relatively high in comparison to the liquid oils that were tested. But the Smart Balance begins to boil at a much lower temperature, 72°C, with large bubbles and spattering which could be dangerous. It also leaves a significant amount of black residue in the pan.

The canola, soybean and olive oils exhibited similar characteristics to each other while heating up, and all three auto-ignited in the average range of 400-435°C. The olive oil could withstand higher temperatures, auto-igniting at 435°C. The canola oil auto-ignited a little lower, at 424°C and the soybean oil auto-ignited at the lowest temperature, 406°C.

The chemical composition of the oils could likely point to factors contributing to auto-ignition temperatures. From Table 1, the olive oil had the lowest amount of polyunsaturated fat, .67 g, and auto-ignited at the highest temperature. The soybean oil had the most amount of polyunsaturated fat, 2.67 g, and auto-ignited at the lowest temperature. This could point to a correlation between chemical composition and auto-ignition temperatures.

This experiment was repeated using fairly common household cooking oils, and could furthermore be repeated to provide data for less-common cooking oils. The auto-ignition temperatures could be compared and might point to a certain type of oil as being safer than others if it has a relatively high auto-ignition temperature, or if it does not auto-ignite during the test.

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