Detection of Abnormal Operating Conditions in Electric Clothes Dryers

DRAFT

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Executive Summary

Electric and gas-fueled clothes dryers are associated with a large number of fire incidents in the U.S. In 1999, there were an estimated 14,600 clothes dryer fires, resulting in less than 10 deaths, 300 injuries, and $86.8 million in property damage[1]. With approximately 80 million clothes dryers in use in the U.S.[2], and an average life of about 13 years, a large potential for future fire incidents exists.

The operation of a clothes dryer involves unattended operation, high temperatures, high voltages and currents, and a potential fuel source (e.g., the materials being dried). Since these conditions are intrinsic to clothes dryer operation, any attempts to reduce the consumer risk associated with this product must take these factors into account.

An exploratory project was undertaken by the U.S. Consumer Product Safety Commission (CPSC) staff to examine how sensor technology could be applied to clothes dryers with the intent of detecting abnormal operating conditions. The CPSC Sensor Technology Clothes Dryer Project was initiated to apply sensor technology to an electric clothes dryer with the intent of demonstrating that:

1) The application of new and emerging sensor technologies can be a means of detecting consumer hazards.
2) The use of multiple sensor inputs of different types can be used to distinguish an incipient hazard condition.
3) Condition-based monitoring can be used to assess clothes dryer operation outside of normal ranges.

A set of abnormal testing conditions or conditions that would lead to abnormal operation was developed and used during the testing. These conditions were: an overfilled drum, an electric coil failure, a blocked lint screen, a blocked exhaust duct, air leaks, the presence of combustible vapors, smoldering combustion, flaming combustion, and spontaneous combustion.

Twenty-three sensors were installed in an electric clothes dryer. During normal and abnormal operation, sensor outputs were recorded and analyzed. The testing showed the feasibility of using sensors for detecting non-normal clothes dryer operation.

Each of the nine defined abnormal test conditions was uniquely identifiable by examining the sensor outputs. From one to three sensors were required to identify a particular test condition. Discrimination of normal from abnormal testing conditions usually depended on discerning a change from previously established typical values. Depending on the magnitude of "abnormality" in the testing parameters, the sensor response changes were small or large.

[1] Miller, David, Smith, Linda, Greene, Michael, "Table 1, Estimated Residential Structure Fires, Selected Equipment 1999," *1999 Residential Fire Loss Estimates*, Directorate for Epidemiology, U.S. Consumer Product Safety Commission, 2003.
[2] Appliance.com, 2002.

The experiments showed that it is possible to use combinations of different sensor types (sensor fusion) to detect abnormal clothes dryer operation. For most of the tests involving abnormal conditions, multiple sensor types were required to identify the specific state of the clothes dryer. In these tests, multiple combinations of various sensor outputs were capable of identifying a particular test condition. Clothes dryer product designers could use this flexibility in formulating new systems with wide fault coverage.

For small magnitude or long-term changes, condition-based monitoring is one technique that may generate useful information on the state of clothes dryer operation. For example, the exhaust airflow variable was sensitive to many types of abnormal operation. Often however, the amplitude of the change from normal conditions was small. Also, the test parameters represent conditions that may take a very long time to develop so that each successive dryer use only incrementally changes the sensor output from its previous value. Condition-based monitoring techniques hold the promise that hard-to-detect conditions may be discernible in a clothes dryer application. Initial values could be established for the parameters being monitored that are specific to the product and its installation. Subsequent appliance operation would generate new values that are then compared to their initial readings. Low-amplitude trends occurring over a long period can be distinguished from ordinary run-to-run variations by accumulating and comparing many readings. Expected long-term performance can then be compared to actual long-term operation to detect conditions that may be discernible in a clothes dryer application.

The testing on this electric clothes dryer shows some of the potential of using sensors in appliances to reduce consumer hazards. To more fully realize that potential, future research should focus on characterization and performance optimization of any sensors selected for a system design.

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1.0 INTRODUCTION

Electric and gas-fueled clothes dryers are associated with a large number of fire incidents in the U.S. In 1999, there were an estimated 14,600 clothes dryer fires, resulting in less than 10 deaths, 300 injuries, and $86.8 million in property damage[3]. With approximately 80 million clothes dryers in use in the U.S. (Appliance.com 2002), and an average life of about 13 years, a large potential for future fire incidents exists.

The operation of a clothes dryer involves unattended operation, high temperatures, high voltages and currents, and a potential fuel source (e.g., the materials being dried). Since these conditions are intrinsic to clothes dryer operation, any attempts to reduce the consumer risk associated with this product must take these conditions into account.

Prior studies conducted by the U.S. Consumer Product Safety Commission (CPSC) staff[4,5] have investigated the effects of lint accumulation and blocked exhaust vents on the operation of clothes dryers. These reports showed how abnormally high component temperatures could be generated in a clothes dryer with no warnings directed at the consumer. Concurrent with these efforts, CPSC staff researched how new and emerging sensor technologies could be used to reduce hazards associated with consumer products. The sensor technology study[6] identified a variety of sensor types with the potential to reduce consumer product hazards in a variety of products.

In 2002, CPSC staff initiated an exploratory project to examine how sensor technology could be applied to clothes dryers to detect abnormal operating conditions.

2.0 PROJECT DESCRIPTION

2.1 Objectives

CPSC staff conducted a research project to examine how sensor technology could be applied to an electric clothes dryer to reduce potential hazards associated with this appliance. This study was designed to demonstrate the following:

1) The application of new and emerging sensor technologies as a means to detect potential consumer hazards.

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[3] Miller, David, Smith, Linda, Greene, Michael, "Table 1, Estimated Residential Structure Fires, Selected Equipment 1999," *1999 Residential Fire Loss Estimates*, Directorate for Epidemiology, U.S. Consumer Product Safety Commission, 2003.
[4] Lee, Arthur, "*Final Report on Electric Clothes Dryers and Lint Ignition Characteristics*," Directorate for Engineering Sciences, U.S. Consumer Product Safety Commission, 2003.
[5] Kadambi, S., "*Final Report on Electric And Gas Clothes Dryers*," Directorate for Engineering Sciences, U.S. Consumer Product Safety Commission, 2000.
[6] Butturini, Randy, "*Sensor Technologies to Reduce Consumer Product Hazards*," Proceedings of the 54th International Appliance Technical Conference, West LaFayette, IN, 2003.

2) The use of multiple sensor inputs of different types to distinguish an incipient hazard condition.
3) The use of condition-based monitoring to assess clothes dryer operation outside of normal ranges.

2.2 Technical Approach

For this project, an electric clothes dryer was selected and instrumented with a variety of sensors. The dryer was operated under normal and abnormal conditions, during which time the sensor outputs were recorded. Normal testing is defined as ordinary operation without any modifications to the clothes dryer. Abnormal testing involved intentionally modifying the clothes dryer or the load to simulate some conditions associated with lack of maintenance, misuse, improper installation, long-term use circumstances, or component failure. Sensor data were examined to establish the normal operating characteristics of the clothes dryer, and to determine if an abnormal operating scenario or a condition that leads to an abnormal operating scenario could be uniquely identified prior to creating a potential fire hazard.

The instrumentation and testing were used to show that conditions indicating a pre-hazardous condition could be detected before a hazardous condition develops. Alternatively, the instrumentation could be used to detect a potentially hazardous condition in time a mitigating action or to be taken.

2.2.1 Clothes Dryer Description and Operation

The sample clothes dryer used in these experiments is a mid-range model, with a retail cost of about $350. The major components of the appliance consist of a rotating tumbler (or drum), a removable lint screen, an electric heating element, and a blower that creates a slight negative pressure in the drum as it exhausts the heated and moistened air out the exhaust ducting. Figure 1 shows a photograph of this product.

Figure 1. Sample Clothes Dryer Used for Testing

Room air is brought into the clothes dryer and exhausted in the sequence shown in Figure 2. Room air is drawn into the appliance through louvered slots in the back panel. The air enters the heater housing opening and flows across the heating element, which is mounted vertically on the back of the dryer chassis. The heated air enters the rear of the drum interior through a screen on the top left side (as viewed from the front). The air mixes with the tumbling clothes load and exits the drum on the top right side. The (now) moist air passes downward through a chute and across the lint screen, against which most of the suspended lint particles are trapped. The air then enters the clothes dryer blower located at the bottom of the dryer and is pressurized as it passes through the impeller. The exhaust ductwork provides a path for the air to exit the clothes dryer to the outdoors.

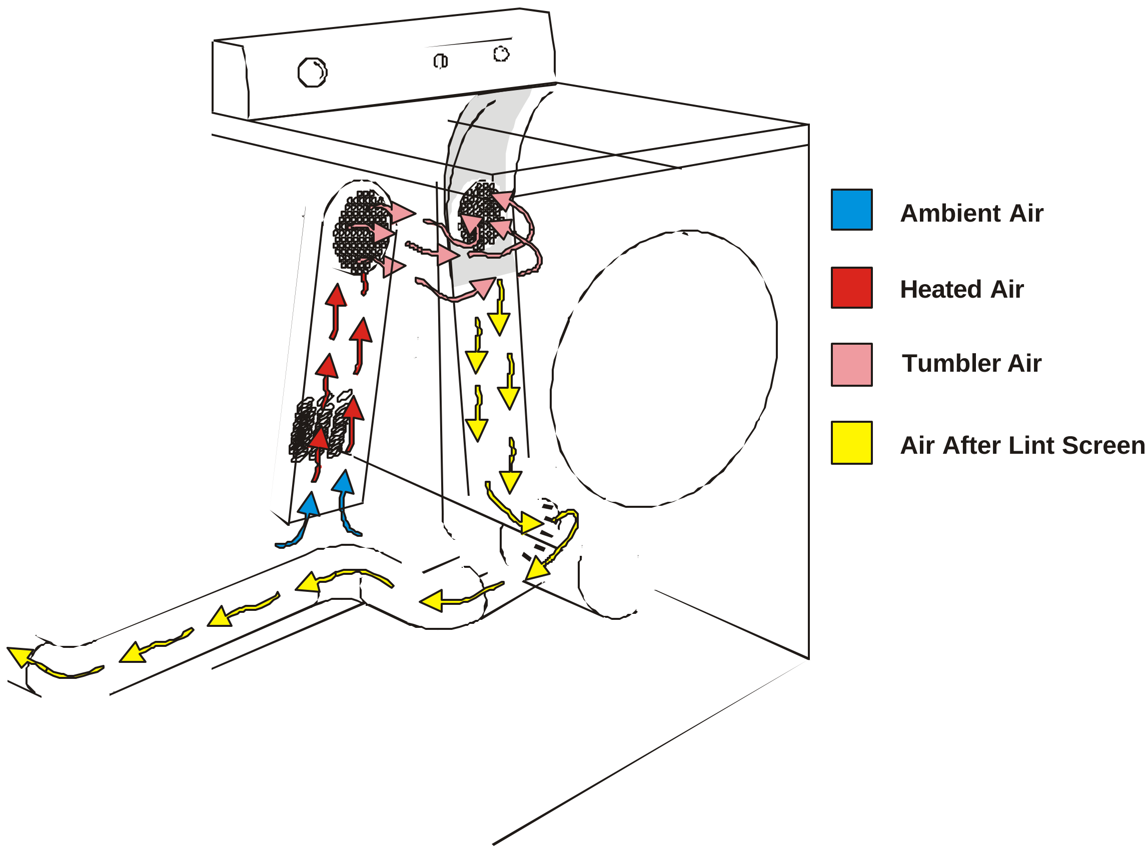


Figure 2. Airflow Pattern in Test Clothes Dryer

The clothes dryer is equipped with two temperature-limiting controls and a temperature-limiting device as shown in Figure 3. The first control is the control thermostat, located just after the blower exhaust. During normal operation, the control thermostat disconnects electric power to the heating element once the air temperature of the blower exhaust reaches a pre-set level. When the air has cooled down, the thermostat resets and the heating element is again energized. The second temperature-limiting control is a high-limit thermostat, positioned at the air intake of the heating element. If the air temperature at the heating element intake is above a pre-set threshold, the high-limit thermostat will activate and de-energize the element. After the high-limit thermostat has cooled down, the thermostat resets and energizes the heating element. The temperature-limiting device is a thermal one-shot, located near the tumbler air intake. The thermal one-shot is designed to activate at temperatures above the set points of the high-limit and control thermostats. When the thermal one-shot activates, the heating element is permanently disconnected from electric power.

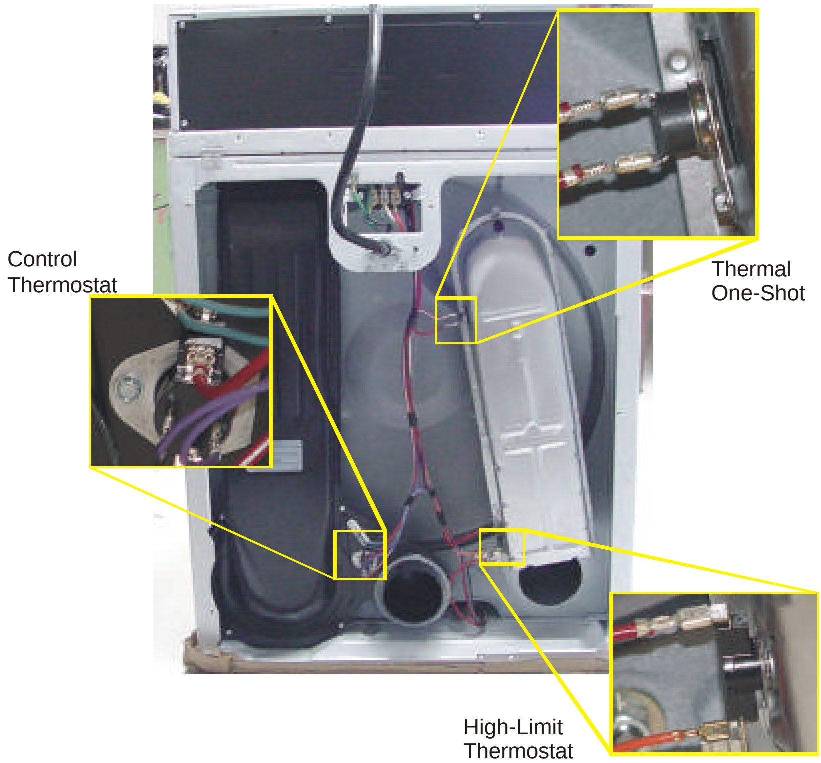


Figure 3. Locations of Temperature Devices

2.2.2 Clothes Dryer Installation

For the tests, exhaust ducting was installed per the clothes dryer manufacturer's instructions. Rigid metal exhaust ducting consisting of about 9 feet of standard 4-inch diameter ductwork with two 90 degree bends was positioned horizontally from the clothes dryer exhaust to the outdoors and was terminated with a 4" cap, as shown in Figure 4.

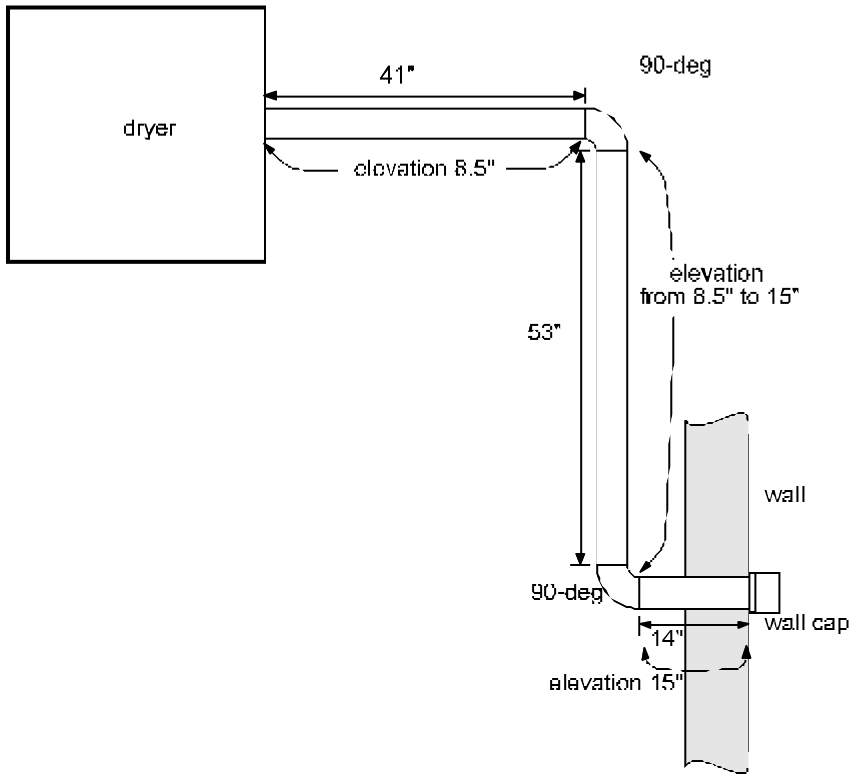


Figure 4. Exhaust Duct Setup Top View

2.2.3 Sensors and Instrumentation

A total of 23 sensors were installed in the sample clothes dryer or in the attached exhaust ducting. Prior to installation, those sensors requiring calibration were calibrated separately.

Six sensors were placed in the clothes dryer exhaust duct, as shown in Figure 5.

- Carbon monoxide. A sensor system with a 0 to 2000 parts per million (ppm) sampling range was used.

- Carbon dioxide. The sensor system used has a 0 to 5000 ppm sampling range.

- Volatile organic compounds (VOC). A broad-spectrum sensor, sensitive to many organic complexes, alcohols, and chlorinated compounds was used. The sensor's dynamic range varies depending on the chemical sensed but is generally in the few hundred-ppm range.

- Airflow was measured using a hot-wire anemometer. The output of the anemometer was scaled to standard feet per minute. That is, the output airflow value represents the same mass transfer of air standardized to 25-degrees Celsius and 1 atmosphere.

- Relative humidity. The sensor was capable of measuring from 0% to 100% relative humidity.

- Air Temperature. The relative humidity sensor was also capable of measuring the exhaust air temperature.

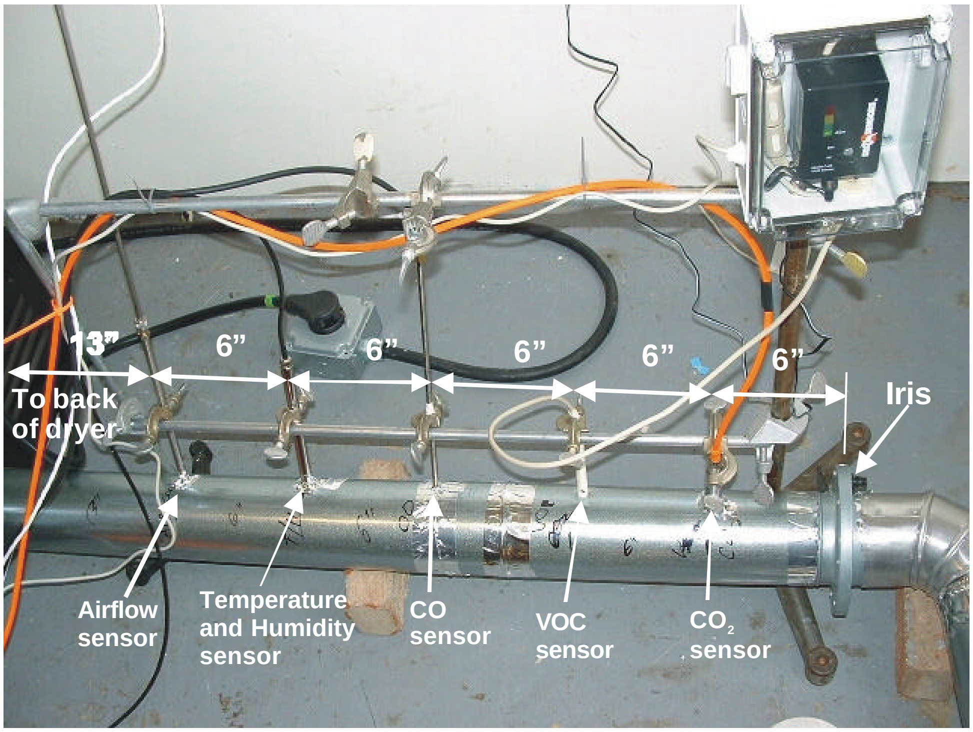
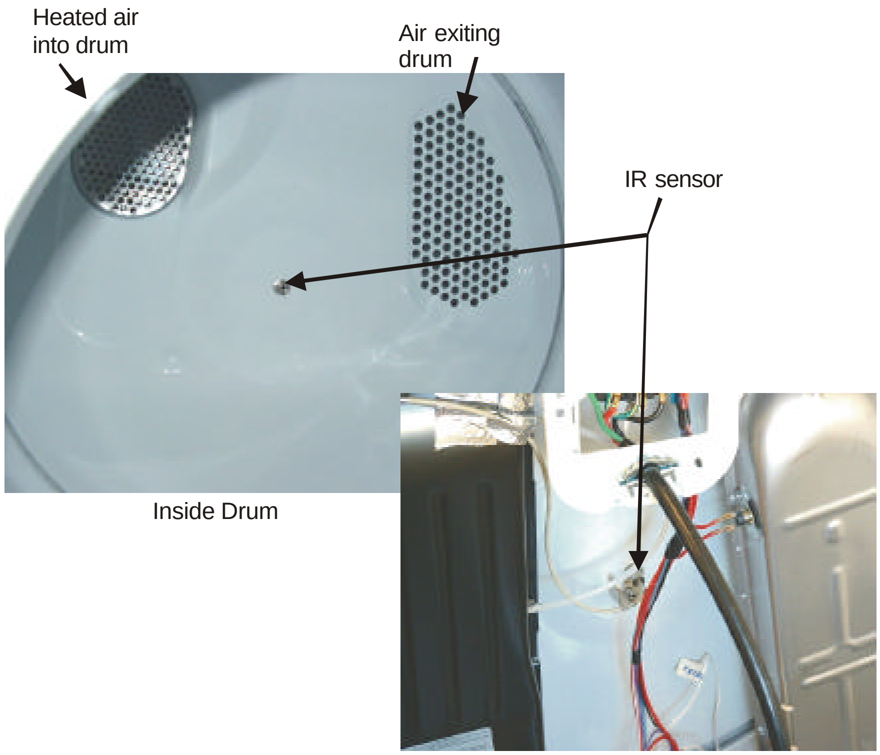


Figure 5. Sensors in the Exhaust

Temperatures in the clothes dryer were measured using K-type thermocouples. Five temperatures were used for thermocouple calibration. Slope and intercept offsets were used to create a straight-line curve fit for each thermocouple. The thermocouples were positioned as follows:

- Blower intake
- Heating element intake
- Ambient room air
- Tumbler intake
- Control panel interior
- Tumbler exterior surface
- Dryer interior outside the tumbler
- Dryer exhaust

In addition to the thermocouples, an infrared (IR) detecting sensor was installed to sense the temperature of the clothing load in the drum, as shown in Figure 6. This sensor was installed in the stationary rear wall of the drum and "looked" into the drum during operation.



Inside Drum

Back of Drum

Figure 6. Infrared (IR) Sensor

Relative humidity was measured in two additional areas: the interior of the dryer (outside the drum) and the room ambient. Each sensor was capable of measuring from 0% to 100% relative humidity.

The air pressure drop across the lint screen was monitored with a differential pressure sensor. This sensor, with a dynamic range of ±1.0 inches of water (±249 Pascals) detected both static and dynamic pressure changes during drying.

Electric currents in the heating element and the blower were monitored with toroid current sensors. The sensors were capable of measuring up to 50 amperes current.

The rotation of the drum was detected through the use of magnets and a Hall Effect sensor. Thirty-two magnets were glued to the clothes dryer drum as shown in Figure 7. The sensor was positioned such that rotation of the drum caused an output pulse to occur whenever a magnet passed in front of the sensor. Hall

Effect sensors are insensitive to dust, temperature and vibration, all normal characteristics of electric clothes dryer operation. The number of magnets passing in front of the sensor for each 2-second sampling period was converted into revolutions per minute of the drum.

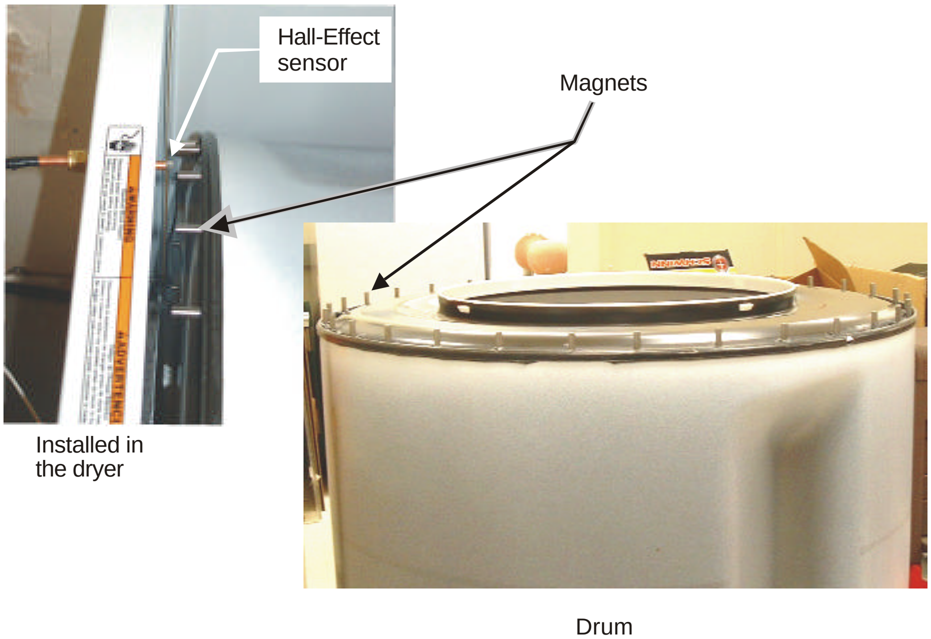


Figure 7. Hall Effect Sensor and Magnets

Motor vibration was sensed with two single-axis accelerometers, attached perpendicularly to the motor mount, as shown in Figure 8. The accelerometers had a dynamic range of 0 to 20 g of acceleration. Eight seconds of data at a 128 Hz sampling rate were collected once each minute. A fast-Fourier transform (FFT) was performed on each data set, resulting in 0.125 Hz resolution over a dynamic range of 0 to 64 Hz.

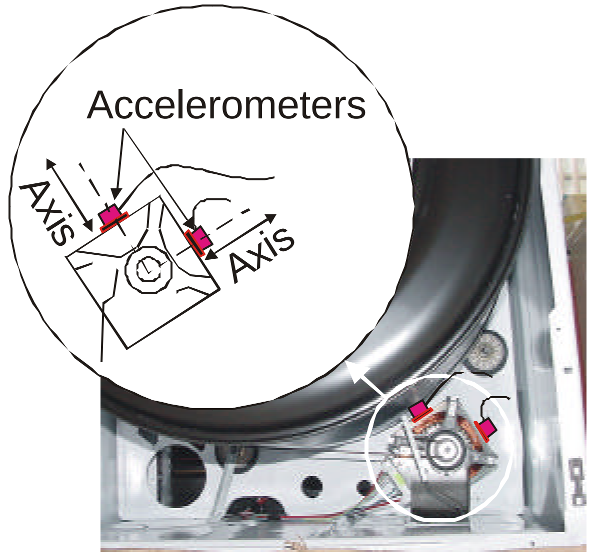


Figure 8. Accelerometers on the Motor Mount

2.2.4 Data Collection Instrumentation

Each sensor output was routed to an analog-to-digital (A/D) converter device. The converter's digitized outputs were recorded by data collection software operating on two desktop computers.

All test runs were conducted for either 15 or 60 minutes. The test run length depended on the test parameters (e.g. dry or wet towel loads). Except for the accelerometers, two sampling rates were employed by the data collection system – 1 sample per second and 1 sample per 2 seconds. For each accelerometer, 1024 samples were recorded each minute during the test at a sampling rate of 128 samples per second. The following table summarizes the data collection timing.

Table 1. Sensor Sampling Rates

Sampling Rate	Sensors
1 sample per second	All thermocouples Infrared detector Carbon monoxide Carbon dioxide Volatile organic compounds Pressure across the lint screen Relative humidity Current toroids
1 sample per 2 seconds	Airflow Hall Effect sensor (rotation)
128 samples per second	Accelerometers

2.2.5 Normal and Abnormal Testing

2.2.5.1 Normal Testing

A standard test was defined for this project: eight cotton towels were washed in a household clothes washer, then dried in the test clothes dryer under the high heat and timed dry setting for 60 minutes. The clothes washer cycle was used (as opposed to just wetting the towels) to generate the lint normally associated with laundering clothing.

Another form of "normal" testing was also assessed. The test clothes dryer used has an "AutoDry" feature, which operates as follows. Instead of operating the system for a fixed time period, The AutoDry setting contains a short-period timer that only advances when the heating element is off. Once the control thermostat activates and de-energizes the heating element, the timer runs until the exhaust air has cooled sufficiently to reset the control thermostat and re-energize the heating element. Then, the timer stops until the heating element cycles off again. Under normal conditions, when the exhaust air is warm enough to cause the control thermostat to de-energize the heating element, the clothing load is almost dry. Setting the timer to "more" dry allows additional on-off cycles of the heating element, whereas setting the timer to "less" dry allows fewer on-off cycles of the heating element. When the timer was set between "more" and "less" dry, the heating element would cycle on-off several times until the timer shut off the dryer.

For some tests, the towel load was not washed before testing. The dry load was typically tested for a 15-minute period.

2.2.5.2 Abnormal Testing

A set of abnormal testing conditions was developed based on incident descriptions and prior observations (see Appendix A). The following abnormal tests were defined for this project.

1. Overfilled Drum. 15 or 20 wet towels were loaded into the drum of the clothes dryer. The system was operated on high heat at a timed dry cycle for 60 minutes.

2. Electric Coil Failure. Normally, about 22 amperes of current (at 240 VAC) flow through the heating element. An element was modified by shorting out a section of the heating coil such that 35 amperes of current were drawn. The power of the heating element was thus increased from around 5280 watts to 8400 watts.

3. Blocked Lint Screen. Normal lint accumulation in the test dryer occurs from the bottom of the screen upwards. A lint screen with 100% of the screen area covered was tested. In addition, lint screens were modified to completely block the lower portion of the lint screen at 25%, 50%, and 75% of the total

area. Even though partially blocked lint screens are not considered abnormal conditions, testing was conducted to determine what percentage of blockage could be detected.

4. Blocked Exhaust Duct. An adjustable orifice was installed in the exhaust duct and was located just before the first 90-degree bend. A blast plate was used to produce a 100% blocked exhaust duct condition. Similar to the partially blocked lint screen, testing was conducted to determine at what percentage the blockage could be detected. The orifice diameter was adjusted to reduce the cross-section of the duct by 25%, 50%, and 75% to simulate a partially blocked exhaust duct.

5. Air Leak. Gaps were created in the airflow path of the clothes dryer to assess their impact on dryer operation and temperatures. The gaps were generally between ¼ to ¾ inch wide. Testing was performed with air leaks in these areas:
   - Between the dryer exhaust and the exhaust ducting
   - At the blower intake housing
   - At the ducting behind the drum and before the blower
   - At the gasket between the drum and the stationary dryer wall

6. Combustible Vapors. Varying amounts of volatile organic compounds were poured onto a section of towel and put into the clothes dryer with either a wet or dry load. The concentration and duration of the chemical vapor in the exhaust flow was monitored during the drying cycle.

7. Smoldering combustion. Smoldering cotton samples were placed in the clothes dryer with and without a towel load. The dryer was operated and the concentration of gaseous combustion products in the exhaust airflow was measured. For those tests with a towel load, only dry towels were used.

8. Flaming combustion. A flaming towel section was dried alone in the drum as the effects of the combustion (gases generated, temperature rise, infrared radiation, etc.) were monitored.

9. Spontaneous Combustion. A measured amount of oil was added to either a wet or dry towel load. The wet loads were dried for 60 minutes. The dry loads were heated for 10 to 15 minutes. The dryer was stopped and the load was left in the drum with the door closed. Temperatures, gases (CO_2, CO), and the output of the VOC sensor were monitored in the drum after stopping the dryer.

2.2.6 Test Materials

The clothes dryer tests were executed with a standard load of eight cotton bath towels. Depending on the testing, the towels were loaded into the dryer after washing in a household clothes washer, or unwashed and dry. Five towel sets were rotated through the testing. All the towels had previously been conditioned by washing and drying several times. Prior to each test, the lint screen was cleaned of any previously accumulated lint.

Modified lint screens were used for some tests. The screens were modified to block areas of the screen with an impermeable material, thus reducing the screen's effective cross-section. Blockages of 25%, 50%, 75%, and 100% were used.

A variety of chemicals were tested in the clothes dryer to determine the VOC sensor's ability to detect their vapors in the exhaust air. Nail polish remover (primarily acetone), denatured ethyl alcohol, lacquer thinner (primarily toluene), and gasoline were tested with wet and dry loads. Soybean oil and linseed oil were used to evaluate aspects of spontaneous combustion in clothes dryers.

Samples of a solid-core woven cotton rope were used to generate smoldering without flaming combustion. Once ignited, the rope samples burned with a glowing ember instead of flames. If a flaming sample was desired, a portion of a cotton towel was ignited with a utility lighter.

2.2.7 Data Analysis

Spreadsheet software was used to analyze the recorded sensor data. Temperature data were generally graphed for simple examination of the maximum values recorded and, importantly, how frequently the control or high-limit thermostats cycled. Averages, slopes, and offsets were similarly calculated for some sensors. As was previously mentioned, accelerometer FFT data were graphed for assessment.

3.0 NORMAL TEST RESULTS

One hundred thirty-three tests were conducted during the project. Of these, 35 tests were normal operation tests with either wet or dry towel loads. The abnormal test sequence was randomized before testing commenced in order to minimize the effects of non-controlled testing variables. As a consequence, the ambient conditions of the clothes dryer varied from test to test, most considerably in terms of initial temperatures and relative humidity. These test-to-test variations were not seen to have a major impact on the ultimate results of any given experiment.

3.1 Temperature

The air temperatures in a clothes dryer are regulated by the control thermostat, directly or indirectly. When the drying cycle for a wet load was started, the heating element was energized continuously. Under normal conditions, the air flowing across the heating element rose to about 174 °C before entering the drum. Evaporation of the water from the wet load cooled the air considerably. The control thermostat sensed the temperature of the air leaving the drum. Only when the load was mostly dry did the temperature of the drum exhaust air increase. When that air reached about 80 °C (for this clothes dryer), the control thermostat activated and de-energized the heating element. The element re-energized when the drum exhaust air cooled to about 54 °C. Thus, for a dried load, the tumbler input air temperature was controlled by the relatively constant airflow and the energy dissipation of the heating element, while the drum exhaust air temperature was regulated by the control thermostat.

Other measured temperatures in the clothes dryer tended to track the rise and fall of the air around the control thermostat, with none being hotter than the tumbler exhaust air (except the drum intake air, as mentioned earlier). The operation of the motor and heat conduction through the drum heated the interior of the dryer chassis, outside the drum, about 15 °C above ambient. The tumbler surface temperature reached a maximum of about 50 °C before the control thermostat activated. Figure 9 shows a representative temperature profile of a wet load of towels being dried. The control thermostat cycled once during the 60-minute test.

In Figure 9, the infrared (IR) sensor temperature profile is not as smooth as the thermocouple temperatures, as expected. The IR sensor's viewing angle has a 2:1 ratio of distance to diameter and detects warm objects in a cone extending from the sensor front. As shown in the setup, Section 2.2.3, the IR sensor was installed at the rear of the drum to observe the load temperature. The tumbling load caused the IR temperature profile to be more erratic. Also seen in Figure 9, the IR profile became more erratic as the load became drier and tumbled more.

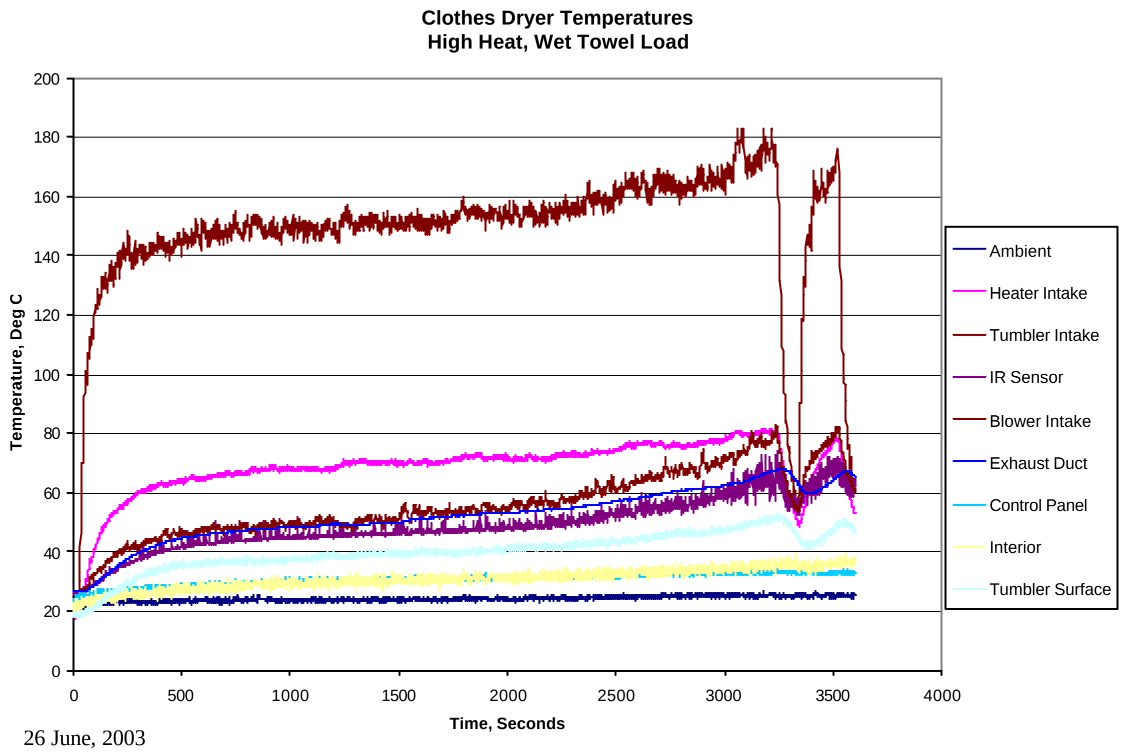


Figure 9. Temperatures During a Drying Cycle

3.2 Relative Humidity

The relative humidity of the exhaust air from the dryer showed a dramatic change from the beginning to the end of a drying cycle and was usually a reliable indicator of the dryness of the clothing load. Typically, the relative humidity of the exhaust air rose from ambient levels to 80% or 90% at the start of the cycle, then smoothly decreased to a minimum of less than 10% by the end of the cycle. The decrease in relative humidity was not linear; there was a rapid decrease from the initial peak level to around 55% to 60% relative humidity during the first ten minutes of the cycle. Then, the rate slowed for the next twenty minutes or so before increasing slightly. Normal cycling of the heating element resulted in small increases in the relative humidity of the exhaust air. This was an effect of the air rapidly cooling after the element de-energized.

The relative humidity of the clothes dryer interior also decreased during a drying cycle. This was mostly due to the increase in the interior air temperature.

The ambient humidity also began to decrease slightly about halfway through the drying cycle. This was mainly caused by the increase in ambient room temperature from heat dissipated by the dryer and the exhaust duct. The test room's dimensions were approximately 15 feet long by 10 feet wide by 10 feet high.

Figure 10 shows the response of the relative humidity sensors during a drying cycle. The control thermostat cycled three times during the test.

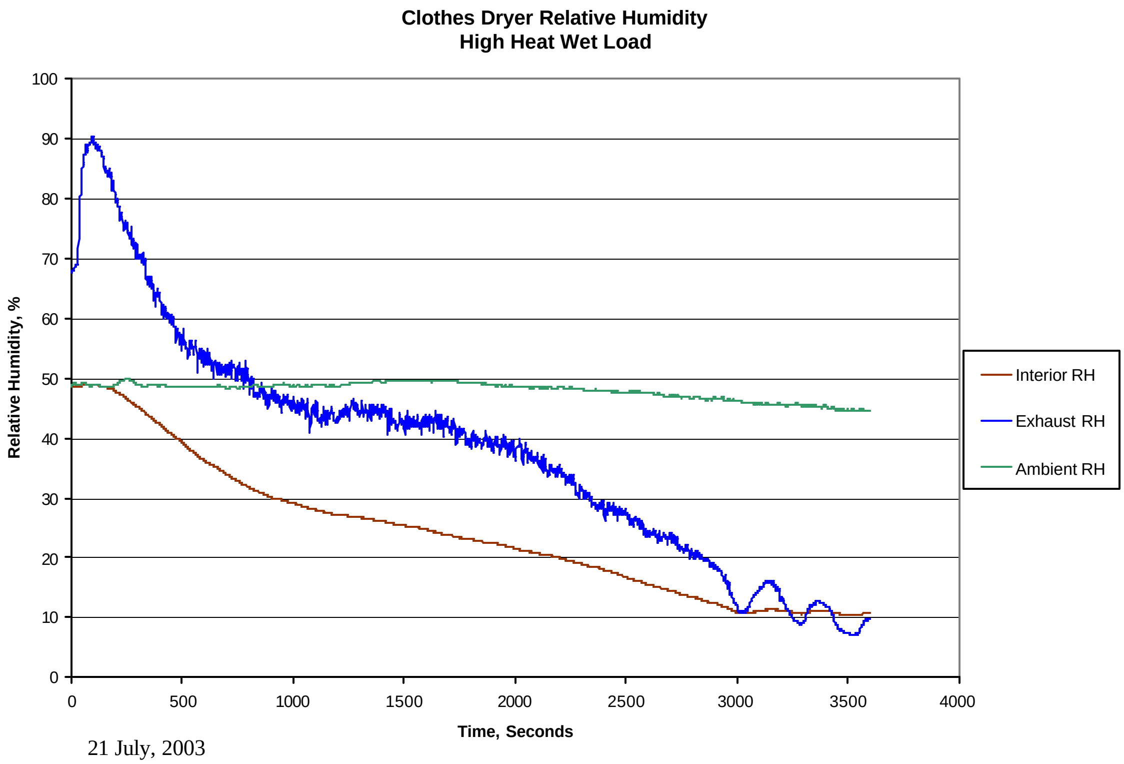


Figure 10. Relative Humidity

3.3 Drum Rotation

A load of wet towels weighed about 22.2 pounds (10.1 kg) from which about 10 pounds (4.5 kg) of water were removed during the drying cycle. This represents a decrease of 45% of the load's weight. This weight change was only weakly reflected in the rotation rate of the drum. For the model clothes dryer tested, the average drum rotation rate was 46.3 revolutions per minute (RPM). Despite the large decrease in the weight, the drum rotation speed increased by about 1 RPM, or 2%, during the drying cycle. With no load in the drum, the average rotation rate was measured at 47.6 RPM. Figure 11 shows a plot of the calculated rotation rate versus time for a drying cycle with a wet towel load.

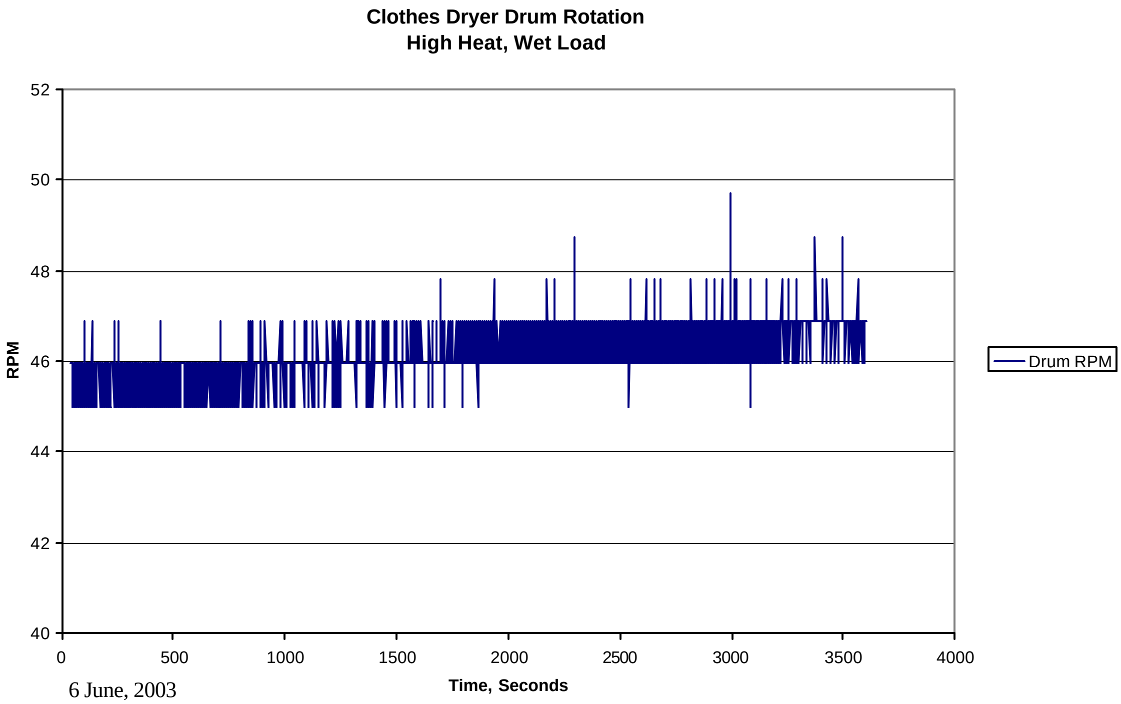


Figure 11. Drum Rotation During Drying

3.4 Pressure Drop Across the Lint Screen

This model dryer has a relatively large lint screen area compared to other designs. The lint screen is shaped into a long rectangle with over 100 in.^{2} (over 660 cm^2) of screen area. The pressure data were measured for one type of dryer load. Other loads of different types and sizes in clothes dryers with different lint screen configurations are likely to show different pressure profiles.

When the clothes dryer was started, there was an immediate increase in the pressure drop sensed across the lint screen. The pressure difference from the front to the rear of the lint screen increased by about 0.025 inches of water (6.2 Pascals, Pa or N/m^2). As the load dried, the pressure typically increased by another 0.043 inches of water (10.6 Pa). Interestingly, the pressure change was not linear. Rather, the pressure difference increased very slowly for about the first 30 minutes then rose more rapidly for the last half of the drying cycle. About one-fifth to one-third of the total pressure change occurred in the first half of the drying cycle, with the remainder accumulating in the latter half. Figure 12 shows a typical pressure profile of a wet towel load during drying.

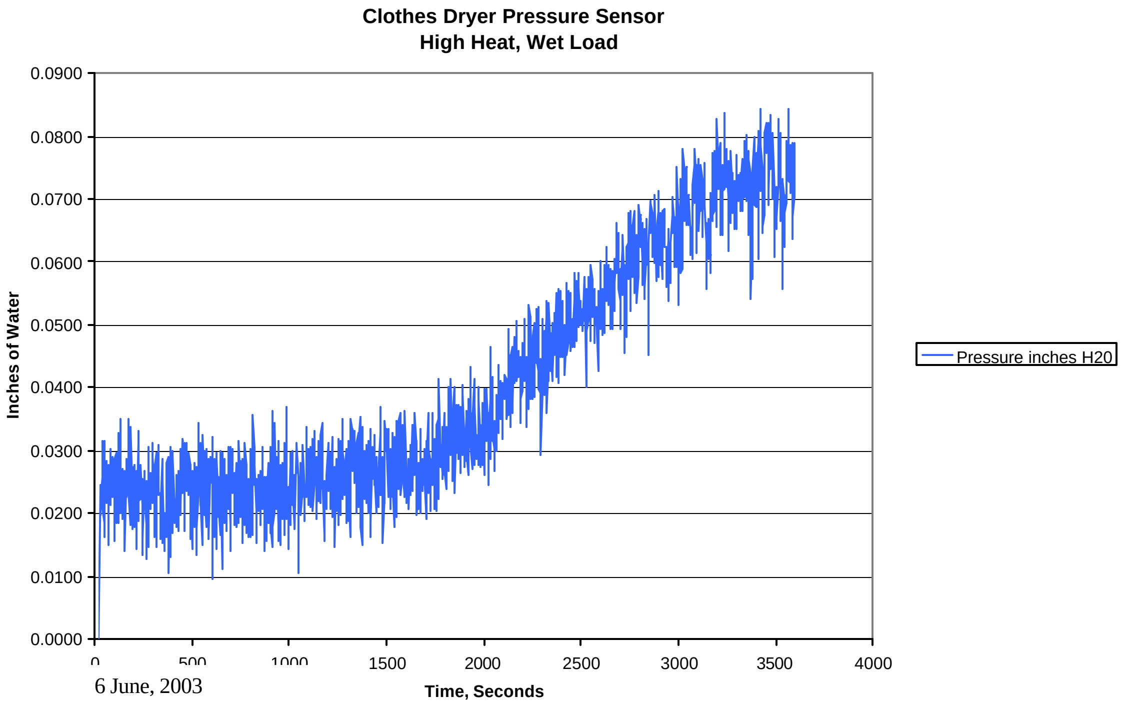


Figure 12. Pressure Drop Across the Lint Screen

The location of the lint screen is also a place with a great deal of air turbulence, shown as reading-to-reading variations that are a significant fraction of the average values.

3.5 Exhaust Airflow

Airflow through the exhaust duct was characterized by a constant flow, unaffected by the accumulation of small amounts of lint in the lint screen. The average exhaust velocity was about 1337 feet per minute (fpm). Figure 13 illustrates a typical flow profile during the drying cycle. The "bumps" at the end of the cycle are due to rapid air temperature changes when the control thermostat cycled the heating element. The anemometer used two resistance temperature detector (RTD) sensors, one heated from 50 to 100 ºC above the airflow's ambient temperature. The other RTD monitored the airflow temperature. The amount of electrical power needed to maintain this temperature difference was the measured output variable. As the airflow temperature changed, the control circuit maintained a constant "over-heat" temperature difference between the heated sensor and the ambient airflow temperature. Since the anemometer is a device that uses heat transfer to determine airflow, rapid temperature changes created temporary artifacts in the calculated flow values. In this sequence, the control thermostat cycled twice.

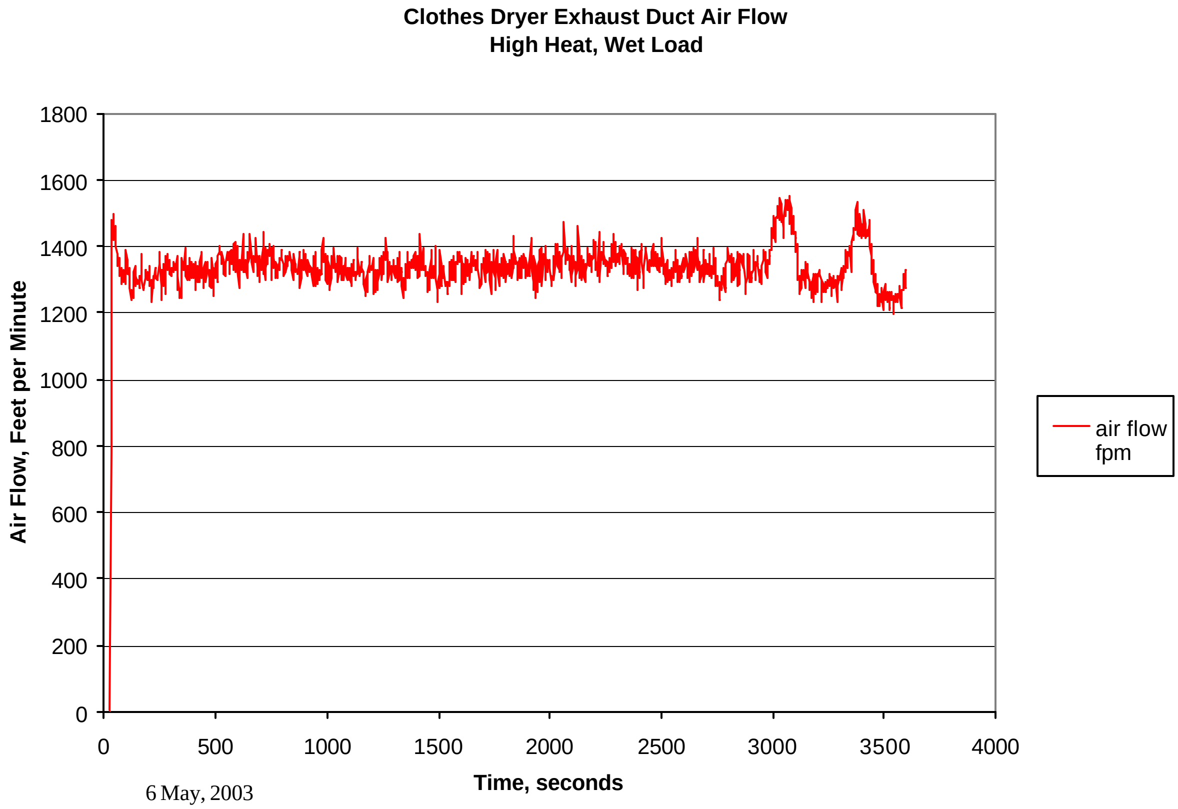


Figure 13. Typical Exhaust Duct Airflow

3.6 Acceleration

Two accelerometers were attached to the motor mount during testing. When the sample amplitude data were processed using a fast Fourier transform (FFT) algorithm, three salient features emerged. First, the rotation of the motor shaft was observed at about 25.5 Hz for the clothes dryer tested. This feature is seen in all the tests involving a rotating drum. The frequency was steady and repeated in all the testing. The second feature was the first harmonic of the motor rotation. This signal appears at double the frequency of the motor shaft rotation, or about 50 Hz. For the motor shaft rotation and its harmonic, all tests and all heat settings, whether involving a towel load or not, generated the same results.

The third feature associated with the FFT was related to the tumbling of the towel load in the tumbler. Vibrations were detected at frequencies below 1 Hz as the drum baffles lifted the load, and the load then fell onto the drum bottom. Due to the erratic nature of tumbling, the peak magnitudes occurred at various frequencies below 1 Hz. Generally, as the towel load dried, there was a tendency to see lower amplitudes and very slightly higher frequencies. This may be due to the relative lightness of the mostly-dry load compared to startup conditions. At the end of a drying cycle, the towels tumbled more uniformly and easily; and they landed on the drum more softly than did wet towels.

Figure 14 shows an example of the FFT of a wet load at the beginning of the drying sample. An eight-second data set was taken each minute for fifteen minutes. The FFT of each data set was computed and plotted.

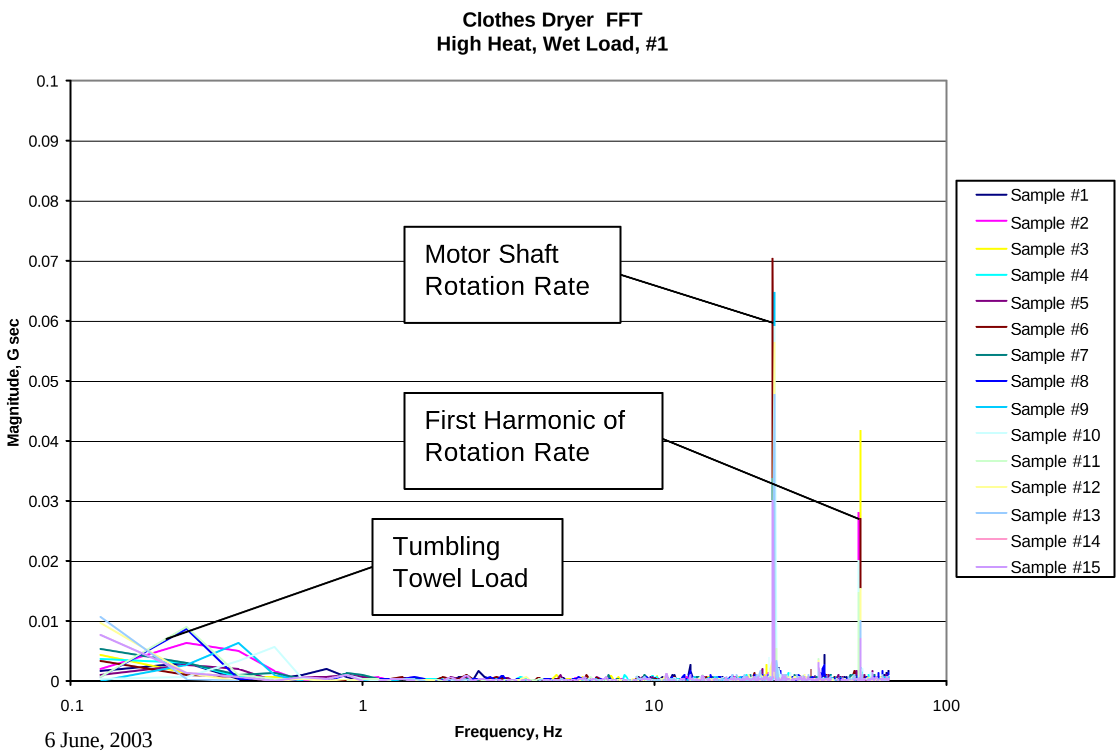


Figure 14. Fast Fourier Transforms of Accelerometer Data

3.7 Electric Current

For the sample clothes dryer, the amperage drawn varies when the heating element cycles on and off. The motor, which rotates the drum and powers the fan impeller, operates throughout the drying cycle. For the sample dryer and the test loads used, the average heating element current was 22.8 amperes; and the average motor current was 4.35 amperes. These values were reasonably constant during the drying cycle. During the tests, the maximum and minimum measured energized current values varied from the test's mean current by less than 10%.

3.8 Exhaust Gases

The sensors utilized to monitor the exhaust air from the clothes dryer during testing were: carbon monoxide (CO), carbon dioxide (CO_2), and a broad range of volatile organic compounds (VOC). For the CO and VOC sensors, regular towel loads (with or without use of a detergent during the wash cycle) generated predictably low signals. For CO_2, the ambient background levels were detected. These values varied from around 330 ppm up to 800 ppm. A number of tests showed a higher CO_2 level at the beginning of the drying cycle, then a decrease as the towel load dried. As seen in Figure 15, the $CO_{2,}$ level rose to around 575 ppm, then decreased to about 420 by the end of the test.

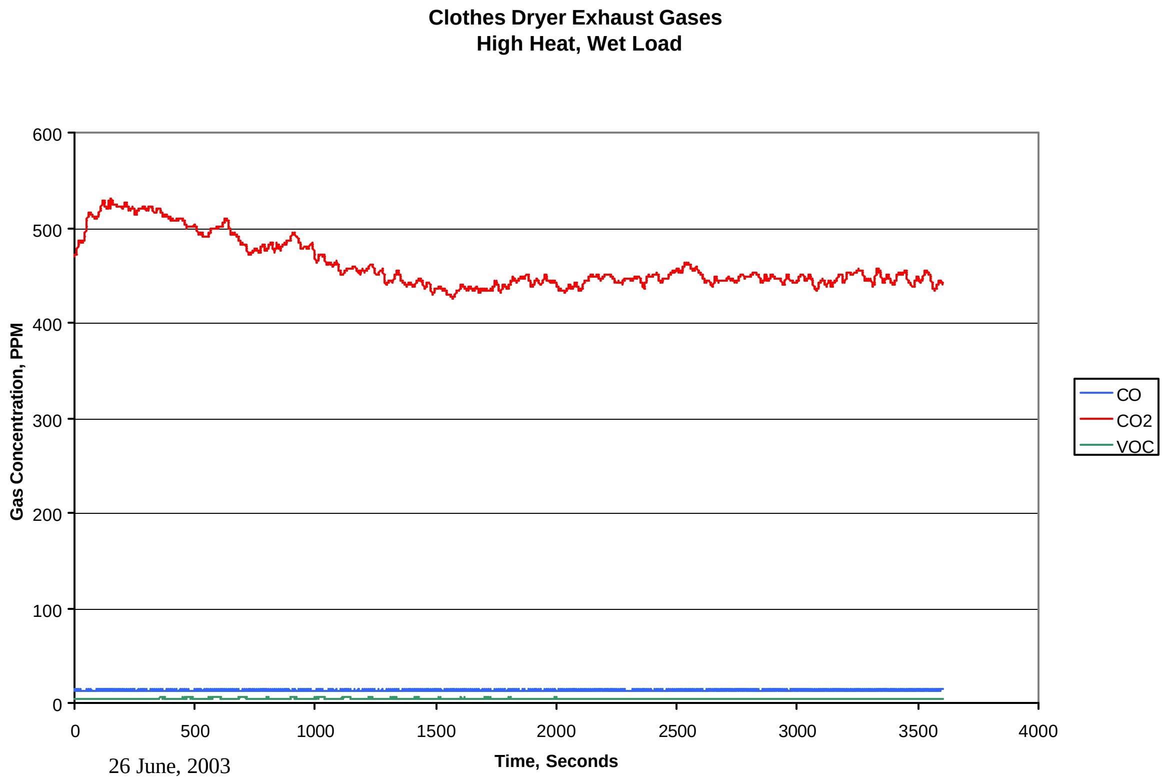


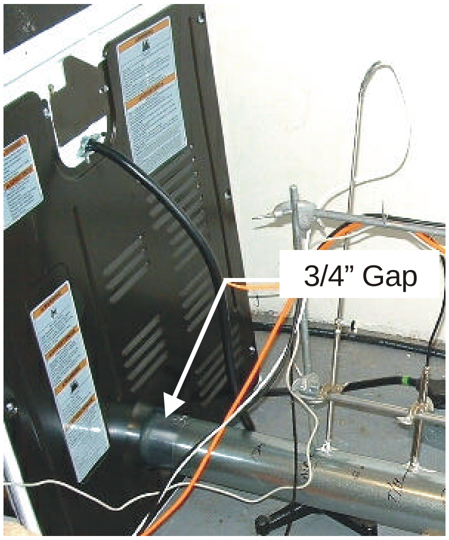
Figure 15. Exhaust Gases During Drying

4.0 ABNORMAL OPERATION RESULTS

The clothes dryer or the load was intentionally modified to simulate some conditions associated with lack of maintenance, misuse, improper installation, long-term use circumstances, or component failure. These abnormal operating conditions were created to determine if the installed sensors could detect the changed operating state. Wet towel loads were then dried in the modified clothes dryer. Every sensor was monitored for every test. Not every sensor manifested a difference between normal and abnormal operating conditions. The following is a listing of the abnormal testing conditions and those sensor outputs that changed from their average values. If a sensor output is not discussed for a particular test, that sensor generated outputs consistent with normal operation.

4.1 Exhaust Duct Air Leak

For this test scenario, the exhaust duct was separated from the dryer by a gap of about ¾ inches. Figure 16 illustrates the test condition.



Shown without gap

Figure 16. Exhaust Air Leak Location

The only observed effect of this type of abnormal operation inside the clothes dryer was that of the relative humidity inside the chassis but outside of the drum. The interior relative humidity at the end of the drying cycle was 34%. Normal operation results in an interior relative humidity of about 20%, even for high humidity ambient conditions. In this circumstance, humid exhaust air was leaking into the dryer interior from the blower output. Figure 17 shows the relative humidity of the exhaust air leak test, the relative humidity of an average of normal operations, and the relative humidity of a normal test with high ambient humidity.

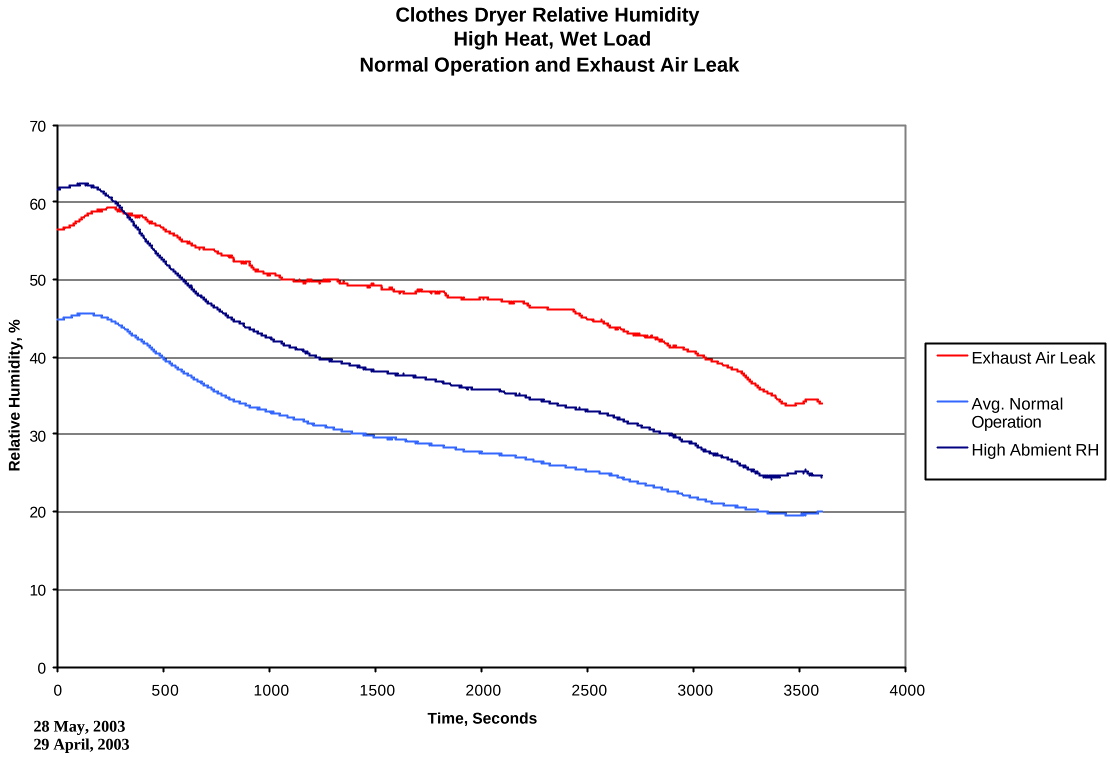
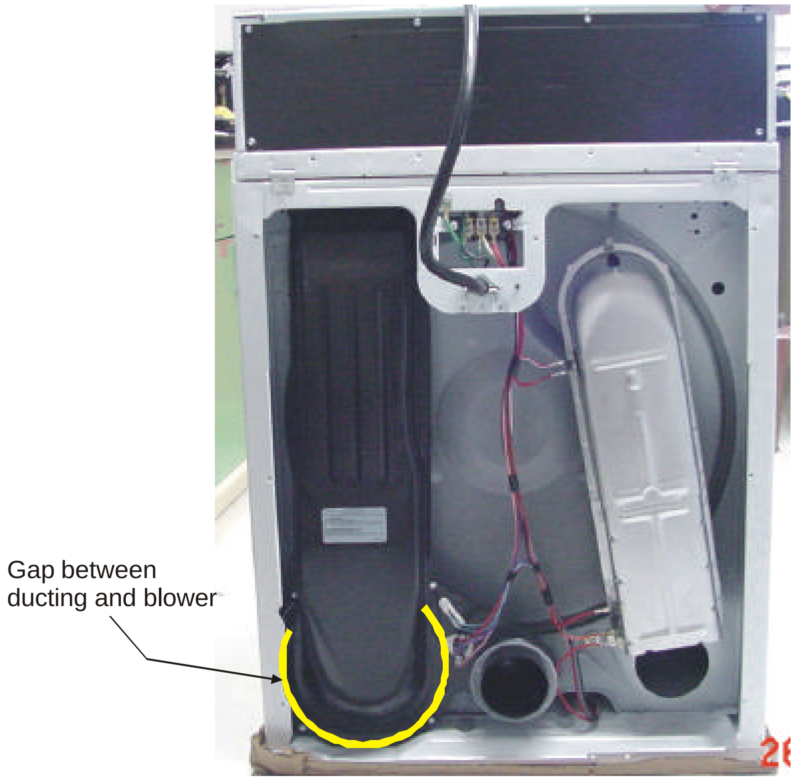


Figure 17. Relative Humidity

The airflow in the exhaust duct decreased from a normal value of about 1337 fpm to about 1150 fpm, or –14%. This decrease represents the specific testing conditions and the low flow resistance of the exhaust ducting. If the airflow sensor was located in a different area of the air stream within the dryer, the flow measurements would likely have been different.

4.2 Blower Intake Air Leak

A ¼ inch gap was created at the bottom of the ducting that directs air from the tumbler to the blower. Figure 18 shows a picture of the leakage path.



Shown without back cover for clarity
Yellow highlight represents location of air leakage

Figure 18. Blower Air Leak Location

Air leaking into the blower at its intake resulted in higher than normal measured temperatures in the dryer. A temperature of 200 °C was recorded at the tumbler intake, or about 25 °C higher than the typical value. Similarly, other temperatures in the "upstream" side of the blower were higher than normal by about 20 °C. The air at the heater intake was measured at 100 °C. Downstream of the leak, temperatures were generally lower than normal. The control thermostat only reached a maximum temperature of about 70 °C, lower than its activation temperature.

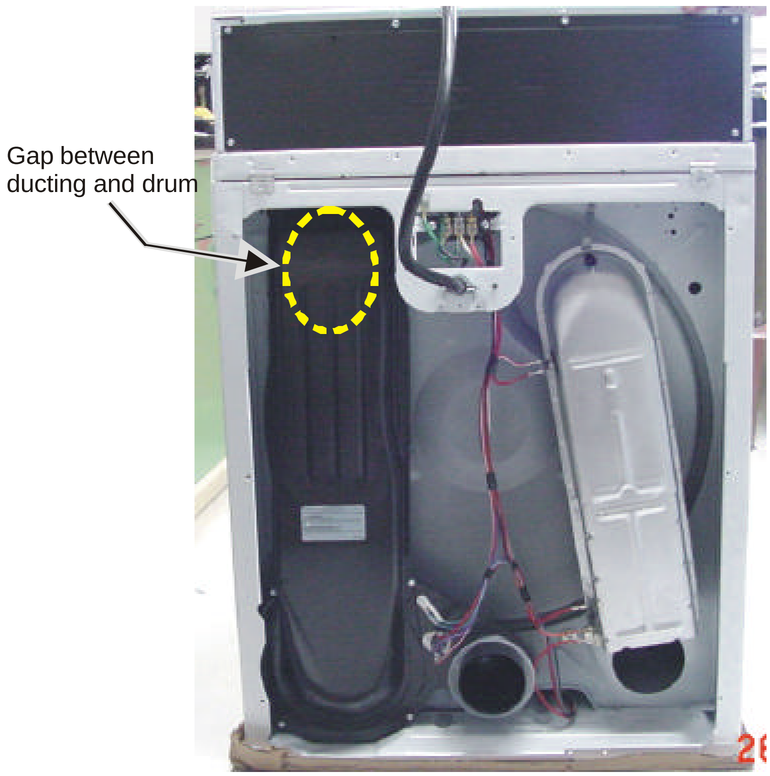
The effect of the air leakage on temperature in this area is twofold. First, the airflow across the heating element is reduced, resulting in a higher operating temperature. Second, the leaking air had the effect of cooling the area around the control thermostat, with the consequence that it never activated during the drying cycle. If the clothes dryer were operating in the Auto Dry mode, the unit may never cycle the heating element on and advance the timer; thus, it may never shut off.

The gap created at the blower intake did not appreciably change the measured airflow through the exhaust. Only one size air leakage gap was tested. Had the leakage gap been larger, the effects on airflow may have been observed as an increase in the airflow.

Relocation of the airflow sensor from the exhaust duct to the lint screen area would likely have increased its responsiveness to blower intake air leaks.

4.3 Air Leak in the Area Behind the Drum

Similar to the air leak created at the blower intake, a gap was created between the stationary tumbler rear wall and the ducting to the blower. The gap was ¾ inches wide on the right side (as seen from the rear) and ½ inches wide on the left side. Figure 19 shows the testing set-up.



Shown without back cover for clarity
Yellow highlight represents location of air leakage

Figure 19. Air Gap Behind Drum

Several sensor outputs changed when a load of towels was dried under this condition. The temperature at the tumbler input increased by 26 °C, or about 16%. Again, this is probably due to the reduced airflow across the heating elements. During the drying cycle, only about one-half of the normal change in the pressure difference across the lint screen was observed. The differential pressure change during this abnormal test was 0.021 inches of water (5.2 Pa), compared to a expected value of 0.043 inches of water (10.6 Pa).

The air leakage resulted in a large increase in the exhaust duct airflow. The airflow increased to about 1600 fpm, or 12% above the typical value. The change in airflow through the tumbler also prevented the wet towel load from drying fully. The exhaust air relative humidity only dropped to 47% during the drying cycle. The combination of cooler ambient air and a smaller-than-normal amount of air from the drum, saturated with water, kept the exhaust relative humidity high.

4.4 Drum Gasket Air Leak

The felt gasket located between the rotating drum and the stationary rear wall was folded back to create an air leak between the two components. This created an approximately ½ inch gap. Figure 20 illustrates this arrangement.

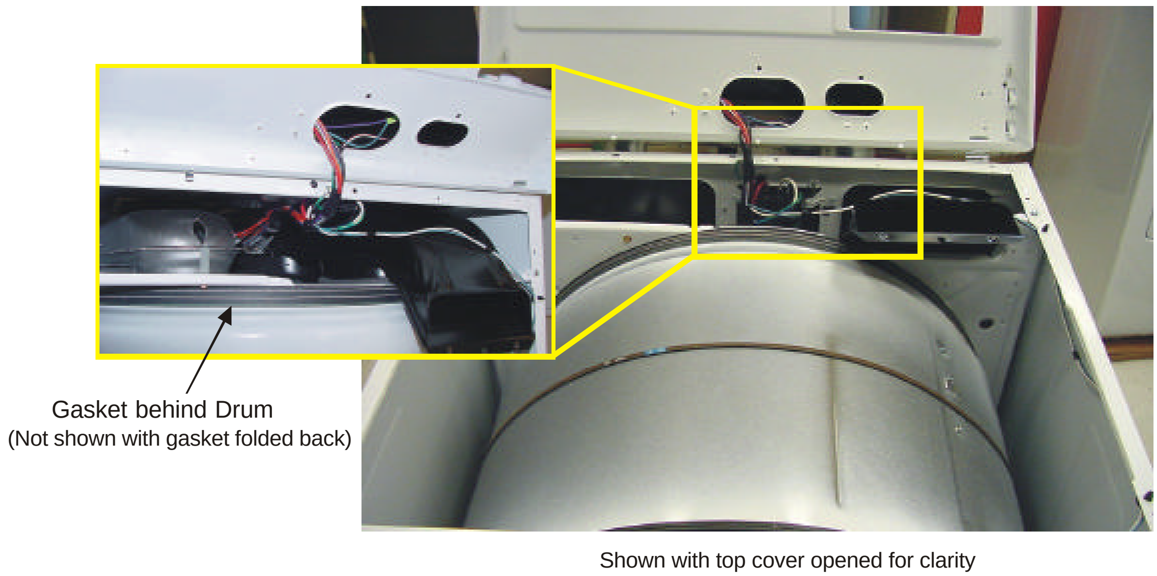


Figure 20. Drum Gasket Air Leak Location

The change in airflow for this abnormal condition resulted in very high temperatures measured at the tumbler intake and relatively low temperatures measured “downstream” from the tumbler. The temperature around the heating element was hot enough to cause the high limit thermostat to cycle. The tumbler intake air temperature reached as high as 240 °C, or 50% above the normal temperature for this area. Elsewhere in the clothes dryer, temperatures of about 70 °C were observed – 10 °C less than their usual values. In a manner similar to other air leakage conditions, the reduced airflow across the heating element, combined with a constant power output, combined to overheat the air around the heating element.

The average exhaust duct airflow with a gasket air leak was about 1450 fpm, or 8% higher than the typical value. This follows the trend of air leaks inside the clothes dryer showing as an increase in the exhaust duct airflow.

Besides providing a seal between the rotating drum and the wall, the drum gasket helps support the drum. When the gasket was folded back, the drum rotated roughly and noisily. During each rotation, the Hall Effect sensor was unable to detect several of the drum magnets when the sensor-to-magnet spacing exceeded the maximum allowed for accurate sensing.

4.5 Exhaust Duct Blockage

The orifice in the exhaust duct was adjusted to create restrictions of 25%, 50%, 75%, and 100%. Wet towel loads were dried under these conditions while the sensor outputs were monitored. At a 25% blockage, sensors did not detect any changes in the operation of the clothes dryer when compared to normal (unblocked) conditions. Above 25% blockage, several sensor outputs changed.

At 50% blockage, the high limit thermostat was at an elevated temperature but not high enough to activate. The peak temperature of the high limit thermostat was recorded at 185 °C, or 6% above average. The control thermostat temperature increased by only 3 °C. When the blockage was increased to 75%, the system quickly started cycling on the high limit thermostat instead of the control thermostat. The cycling was rapid enough to keep the air in the area of the control thermostat cooler than normal. The control thermostat air temperatures were only slightly above ambient values. Figure 21 shows the high limit and control thermostat temperatures during a test with the exhaust duct blocked 75%. This graph is characteristic of a system cycling on the high limit thermostat. Under these conditions, the tumbler intake air temperature is higher than normal and there are many cycles in a short period. An exhaust duct blockage of 100% generated similar results.

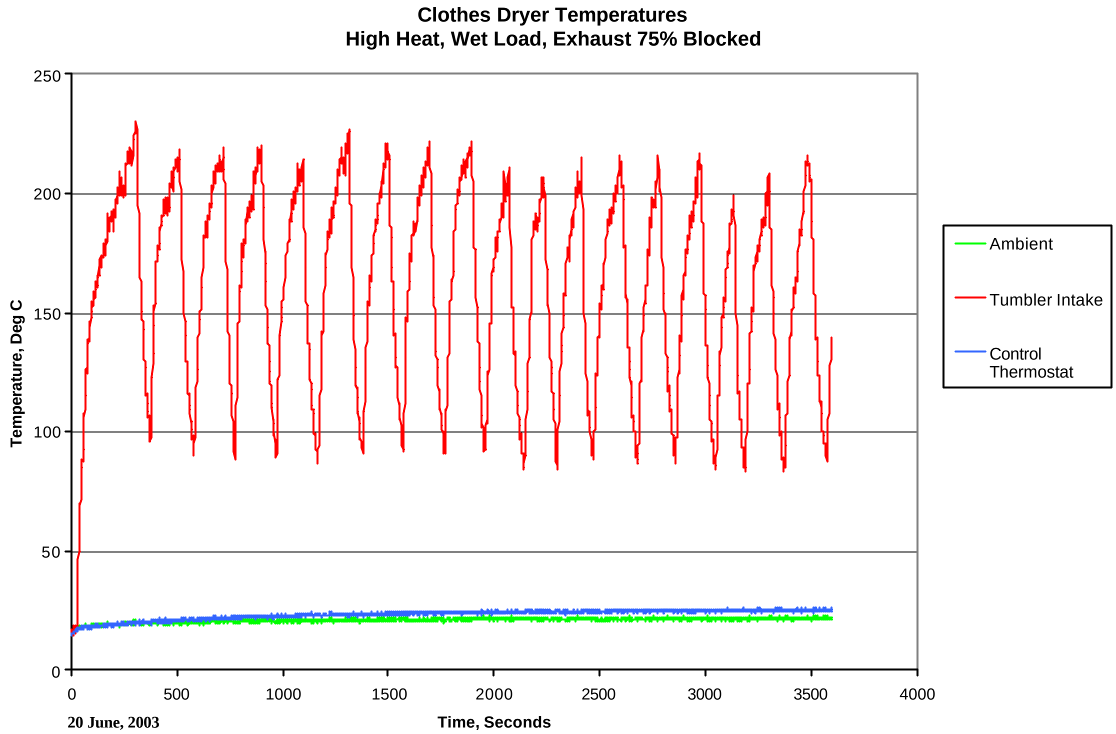


Figure 21. Thermostat Temperatures at 75% Blockage of the Exhaust Duct

Airflow in the exhaust was affected by exhaust duct blockages of 50% and higher. A reduction of airflow by 16% (from 1337 fpm to 1120 fpm) was observed with a 50% blockage. At 75% blockage, the measured flow was only 46% of the average airflow, or 625 fpm. The air in the exhaust was essentially stagnant at 100% blockage.

Differential pressure changes across the lint screen during the drying cycle were apparent at blockages above 25%. A 50% exhaust duct blockage reduced the pressure drop across the lint screen from the average value of 0.043 inches of water (10.6 Pa) to about 0.028 inches of water (6.9 Pa), a decrease of 35%. A blockage of 75% reduced the drying cycle pressure change to 0.0036 inches of water (0.9 Pa), only 8% of the normal value. Fully blocking the exhaust resulted in no measured pressure change across the lint screen.

4.6 Blocked Lint Screen

During normal operation of this clothes dryer design, lint accumulates in the lint screen from the bottom up. To simulate lint screen blockage, lint screens in which the bottom 25%, 50%, and 75% of the surface area of the screen was covered were installed in the clothes dryer for testing. A lint screen with the mesh area totally blocked was also tested.

At a blockage of 25%, the clothes dryer static pressure was markedly higher than during normal operation. The pressure change occurring across the lint screen when the clothes dryer was turned on was about 0.19 inches of water (47.5 Pa). This is six times the pressure change seen with an unaltered lint screen. This pressure change persisted during the drying cycle, resulting in very little pressure change from start to finish.

At higher blockages, the static pressure change also increased. With a 50% blockage, the static pressure change at dryer turn-on was 0.21 inches of water (52.5 Pa). A blockage of 75% generated a static change of 0.31 inches of water (77.5 Pa), and a fully blocked lint screen created a pressure difference of 0.46 inches of water (115 Pa). In each case of lint screen blockage, the static change persisted throughout the drying cycle. Figure 22 shows the pressure changes with successive lint screen blockages.

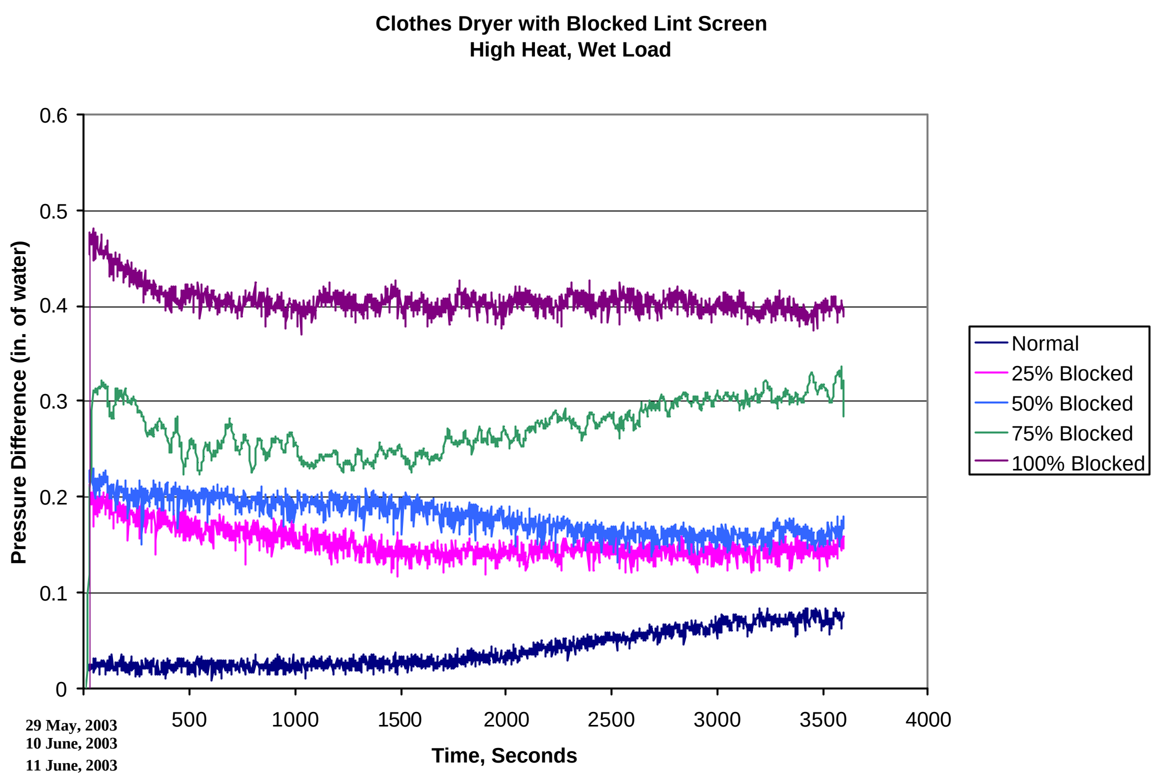


Figure 22. Differential Pressure across the Lint Screen with Successive Blockages

The effects of lint screen blockage on exhaust airflow were more modest. At 25% blockage, the exhaust airflow was only slightly less than expected values. With a lint screen blockage of 50%, the airflow decreased to about 1200 fpm, or 89% of the regular flow. At a blockage of 75%, the exhaust duct airflow had decreased to around 1000 fpm, or 75% of the normal airflow. Even at 100% blockage, a 950 fpm airflow (71% of the normal airflow) was detected in the exhaust duct. This last value may represent the ability of air to leak around the lint screen.

Clothes dryer temperatures were affected by lint screen blockages. No substantive temperature changes were noticed at blockages of 25% and 50%. At a blockage of 75%, the tumbler intake air temperature rose from 174 °C to 190 °C, about 10% above the normal value. The airflow was sufficient to keep the high limit thermostat from activating. At 100% blockage, the clothes dryer system cycled on its high limit thermostat. The tumbler intake air was measured at about 220 °C.

A load of towels was dried with no lint screen installed. This arrangement had the effect of behaving like a large air leak with respect to airflow and temperatures. The high limit thermostat cycled. The airflow in the exhaust was large (about 20% above normal). The pressure sensor did not record as large a static pressure increase as usual, and the pressure difference did not increase during the drying cycle. The missing lint screen had the effect of keeping the relative humidity of the exhaust air high. Cooler ambient air mixed with humid warm air from the tumbler, maintaining a relative humidity above 35% for the duration of the test.

4.7 Overfilled Drum

An increase of 100% or greater in the clothes dryer load changed the output of the pressure sensor significantly but only marginally affected the outputs of other sensors. When either 15 or 20 wet towels were loaded into the tumbler (a load increase of 88% and 150%, respectively), the change in differential pressure during the drying cycle essentially vanished. The 15-towel load pressure change was 0.005 inches of water (1.2 Pa), or 12% of the normal value. The pressure change for the 20-towel load was essentially unchanged from the start to the end of the test.

The temperature of the tumbler intake air was very slightly elevated from normal conditions when the drum was overfilled. The tumbler intake air temperature was 180 °C, or 6 °C higher than typical.

Overfilling the tumbler had a small effect on its rotation rate. With 20 wet towels in the tumbler, the rotation rate decreased from 47.3 RPM to 43.7 RPM, a change of only 8% for 2½ times the weight of the average load. With so many towels in the tumbler, the load did not tumble. Rather, it rotated as a mass with the tumbler.

The airflow through the exhaust was reduced to about 1100 fpm from the average value of 1337 fpm, representing an 18% decrease. This particular model clothes dryer airflow path may explain why a greater decrease was not observed. The air enters and exits the tumbler through holes in the stationary rear wall. With an overfilled drum, the input air entered the tumbler, flowed along the rear wall, then exited to the blower, as illustrated in Figure 23. Only the portions of the towels next to the rear were dried. The remainder of the towel load stayed wet. If the dryer design had the airflow path cross from the rear to the front of the tumbler (and through a lint screen mounted in or below the dryer door), the effects on airflow caused by overfilling the tumbler airflow may have been more pronounced.

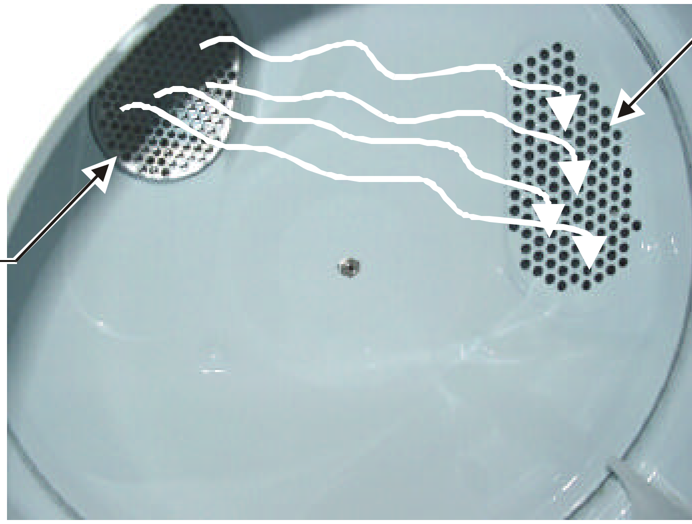


Figure 23. Tumbler Airflow Path

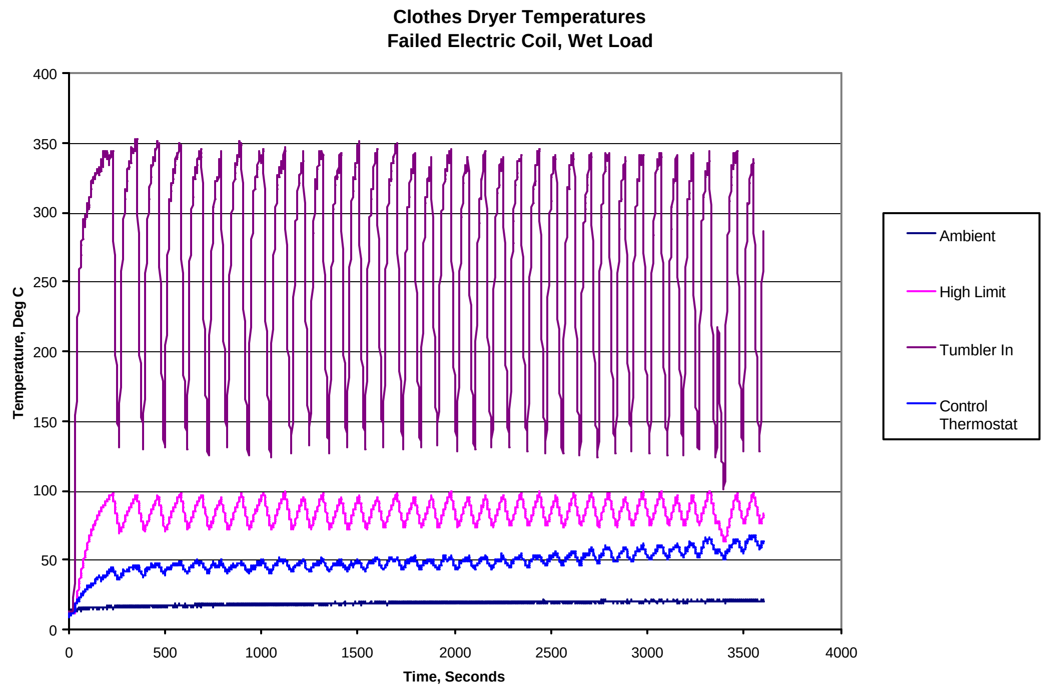
4.8 Electric Coil Failure

An electric heating element was altered to assess how the clothes dryer would operate under excess heating conditions. A section of the coil was short-circuited to reduce its total resistance (and thus increase the dissipated power). Enough heating element remained in the current path to avoid overcurrent conditions. The expectation was that the remaining heating coil would consume more energy and create very hot air entering the tumbler.

The modified electric heating element was installed into the clothes dryer and operated with a normal load of wet towels. The functioning of the dryer was markedly changed with respect to two of the variables measured, electric current and temperature.

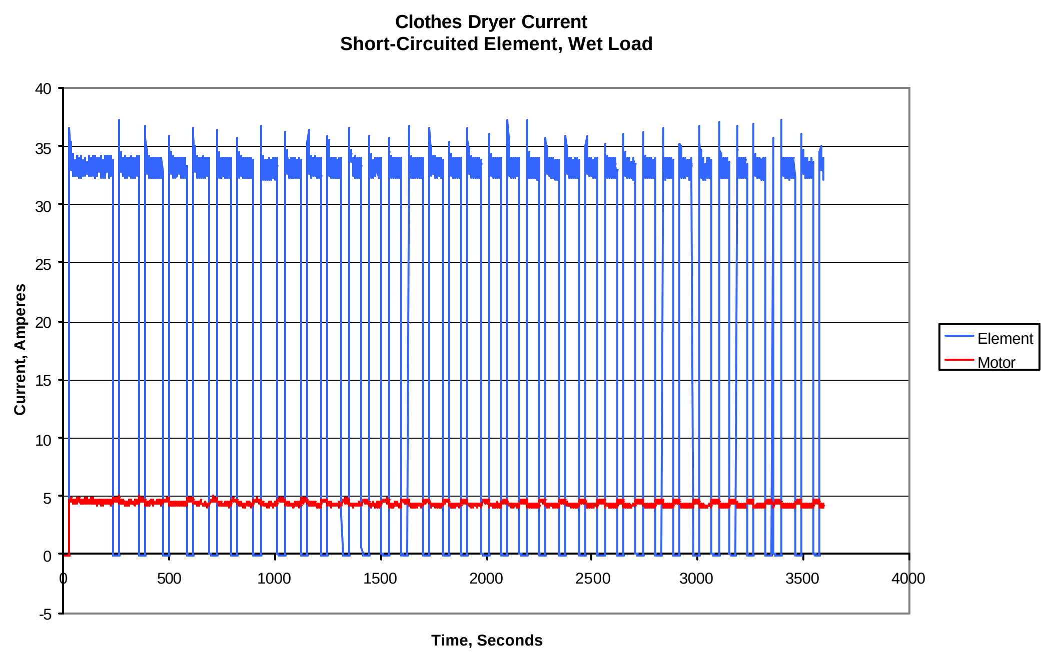
This operating condition was the only one in which the current through the heating element varied from the routine 22 amperes. For this test, the current through the element was 35 amperes when energized. The modified heating element dissipated 8400 watts of heat, a 60% increase over the regular value of 5280 watts. None of the other operating modes tested had any effect on the magnitude of current through the heating element.

When energized, the modified heating element heated the air entering the tumbler very quickly to very high temperatures. At its maximum, the air at the tumbler intake exceeded 350 °C. However, the control thermostat air reached a maximum temperature of only 64 °C. The extra power dissipated by the heating element caused rapid cycling of the high limit thermostat, so much so that the control thermostat stayed relatively cool. Figure 24 shows the temperature response of the clothes dryer under these operating conditions. Figure 25 shows the corresponding current of the heating element cycling rapidly.



17 May, 2003

Figure 24. Modified Electric Coil Air Temperatures



17 May, 2003

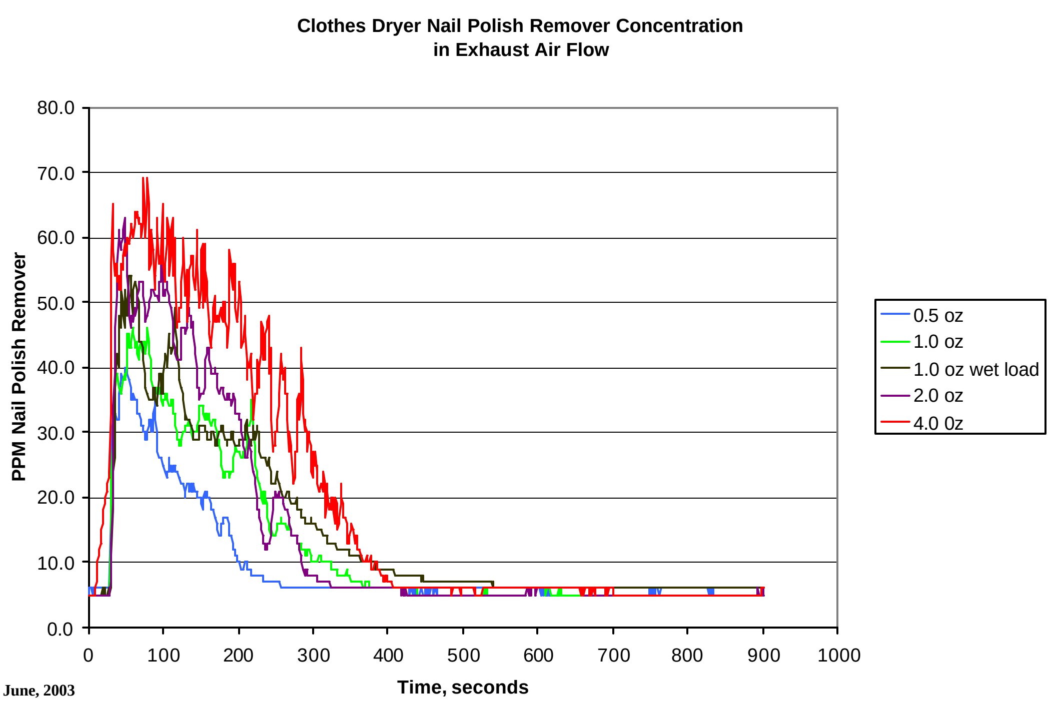
Figure 25. Electric Current in the Heating Element and the Motor

4.9 Volatile Organic Compounds (VOC)

Four different chemicals were tested to determine if the VOC sensor in the exhaust duct would detect their presence. A sample amount of the VOC under investigation was poured onto a small piece of towel and added to the load in the clothes dryer. The load was dried on the High Heat setting. Data collection proceeded for 30 seconds before starting the clothes dryer. Nail polish remover (mostly acetone) and gasoline were tested at 4 amounts, and with wet and dry towel loads. Ethyl alcohol and lacquer thinner (mostly toluene) were tested at a single sample amount for dry loads.

During the tests, all the sensors except the VOC sensor responded normally. The VOC sensor responded quickly to the presence of the test chemical in the exhaust duct. The concentrations were always at low levels and quickly decayed towards background signal levels.

Figure 26 shows the VOC sensor response to nail polish remover. For the nail polish remover, the sensor response very quickly peaked, then declined. After about 7 minutes of operation, the output of the VOC detector had returned to background levels, indicating that no detectable concentrations (more than 5 ppm of nail polish remover) were in the exhaust airflow. Larger amounts of nail polish remover had a small effect on the amplitude and duration of the VOC sensor response. Wet towel loads did not seem to affect the magnitude or duration of the signal as compared to those for dry towel loads. All towel loads tested were dry except for the one wet load noted.



26 June, 2003
30 June, 2003
1 July, 2003

Figure 26. VOC Sensor Response to Nail Polish Remover

Unleaded gasoline was tested in a manner similar to the nail polish remover. Samples from 0.5 oz. to 4 oz. were measured out and added to a small portion of a towel. The portion was added to a dry or wet towel load, data collection was initiated, and the dryer (on the high heat setting) was started at around the 30-second mark.

Components of the gasoline were quickly detected in the clothes dryer exhaust duct. However, the amplitudes of the signals detected were small and their durations were brief. For the highest levels of gasoline tested, between 8 and 10 minutes were required for the sensor output to return to background levels. The concentration of the detected chemicals remained low throughout the tests. Figure 27 shows the VOC sensor response to gasoline. The sensor output was cross-correlated to a gas chromatograph / mass spectrometer analysis of a sample of the clothes dryer exhaust air.

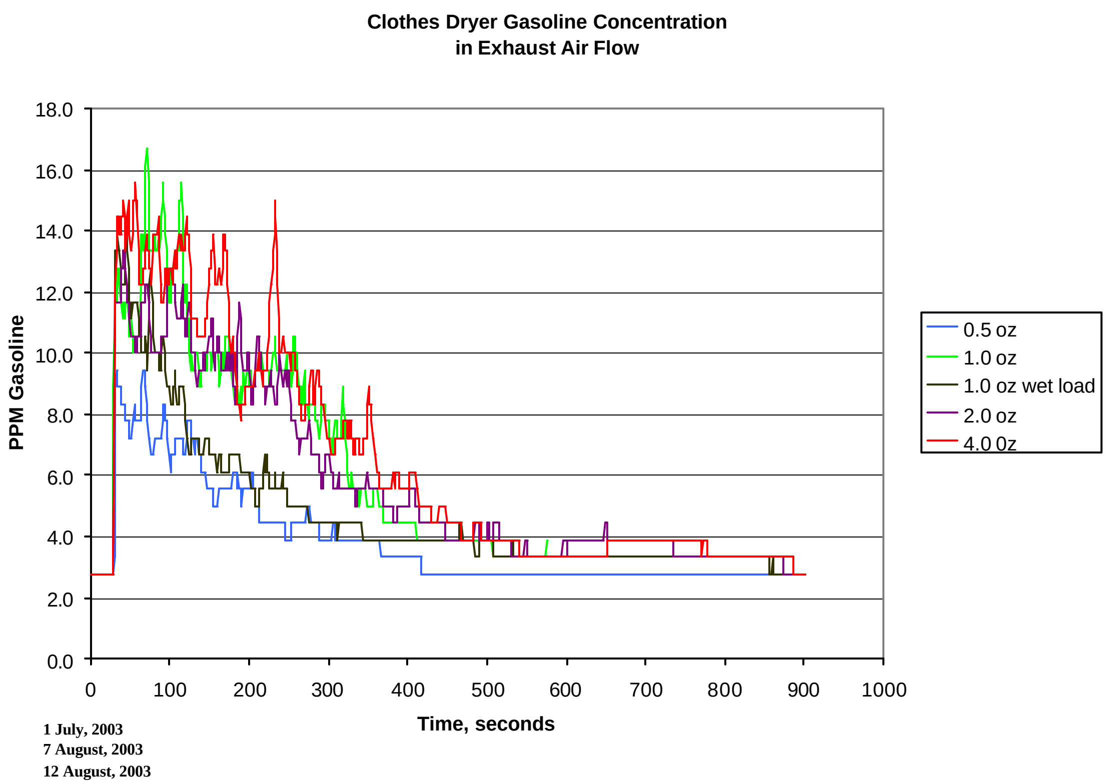


Figure 27. VOC Sensor Response to Gasoline

When 1-ounce samples of ethyl alcohol and lacquer thinner were tested on dry towel loads, the response of the VOC sensor was slightly less in amplitude and similar in duration to that for the nail polish remover.

4.10 Smoldering Combustion

Samples of smoldering cotton rope were placed in the clothes dryer tumbler, as shown in Figure 28. In the first set of tests, from 1 to 4 cotton rope samples were suspended and ignited to achieve smoldering combustion. For the second set of tests, 4 smoldering cotton rope samples were tumbled with a dry load of towels.

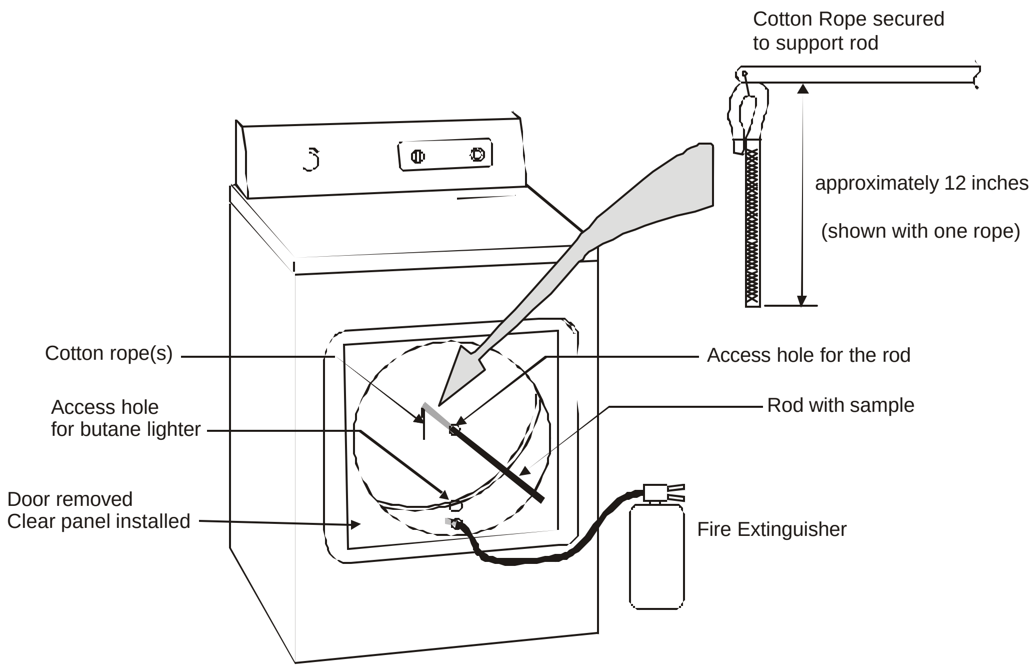


Figure 28. Test Setup for Smoldering Combustion

Of the sensors monitored, the carbon monoxide (CO) and volatile organic compounds (VOC) detectors produced non-normal responses. As seen in Figure 29, increasing numbers of smoldering samples increased the amount of CO detected in the exhaust airflow. Using only one sample almost doubled the response of the CO detector over the background reading. When the dry towel load was tested with smoldering samples, the amount of CO generated increased sharply after a few minutes of operation. The sample towel set had numerous small burns on the terrycloth as a result of contact with the burning embers of the cotton rope samples.

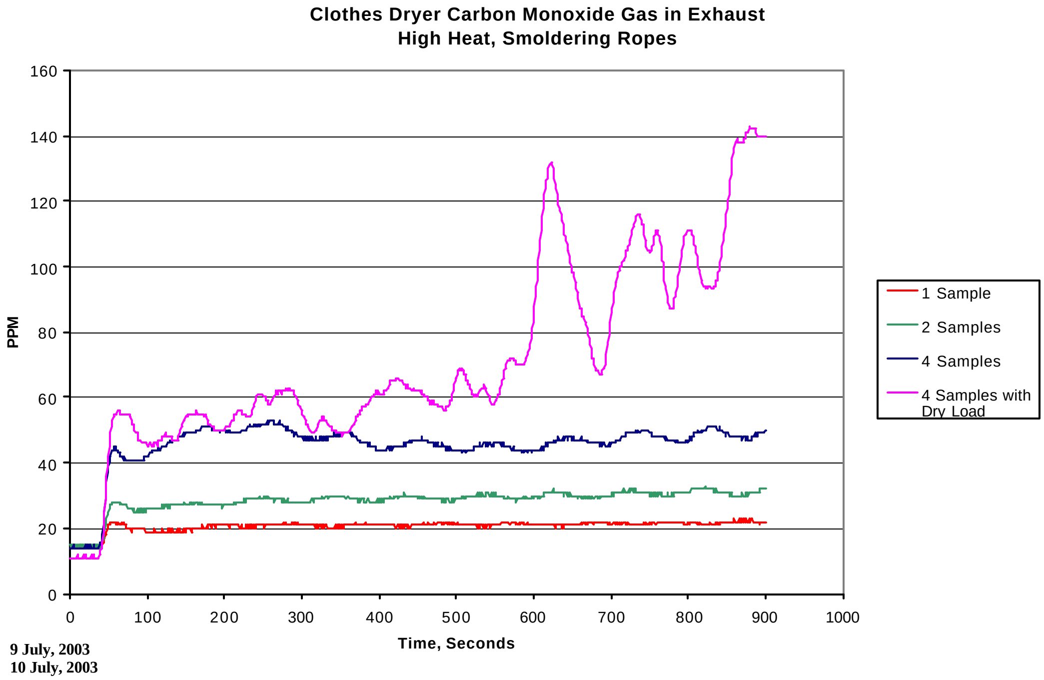


Figure 29. Carbon Monoxide Detection of Smoldering Combustion

The VOC sensor also generated responses similar to those of the CO detector, but at a much lower level. With a background signal of about 5 PPM, smoldering samples generated small magnitude but large percentage changes. Four smoldering samples raised the sensor's response to around 9 PPM. The dry towel load test with four samples also resulted in increased VOC detection levels during the latter portion of the test. Figure 30 shows the response of the VOC sensor to smoldering combustion.

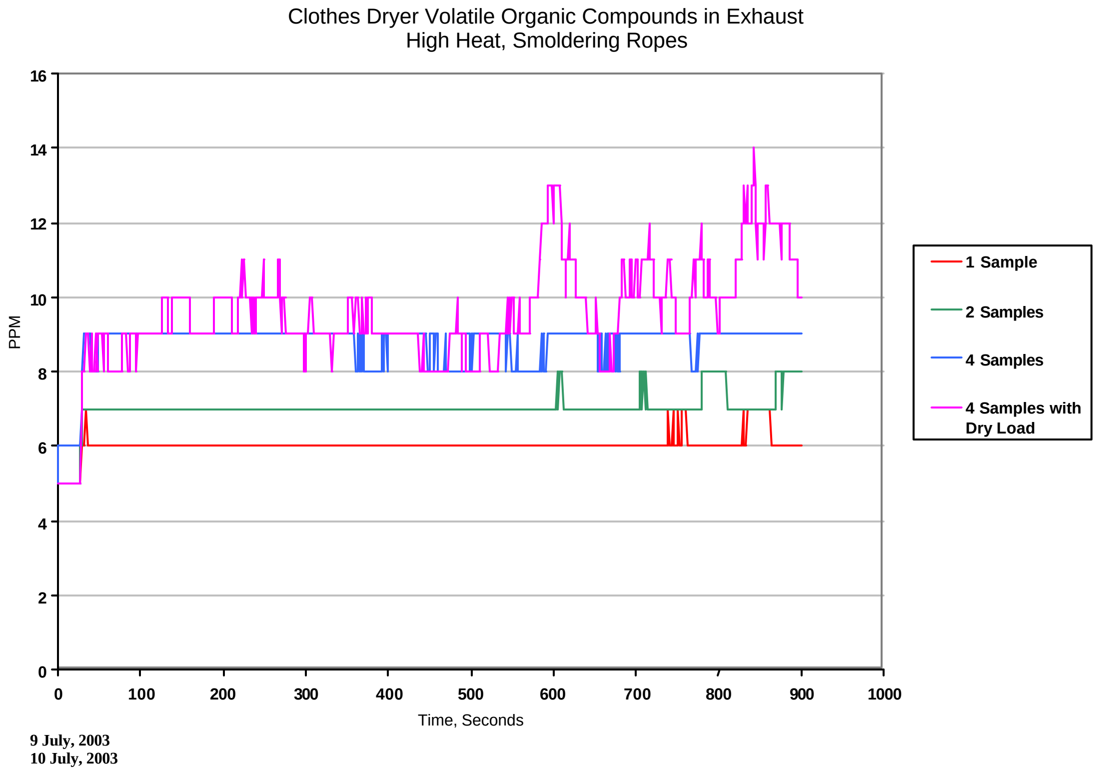


Figure 30. Volatile Organic Compound Detection of Smoldering Combustion

4.11 Flaming Combustion

Towel samples (from 1/16th to 1/32nd of the original towel size) were ignited and suspended in an empty tumbler, in a manner similar to the cotton ropes used in the smoldering combustion tests. After ignition, the clothes dryer was operated with the heating element de-energized for 15 minutes. During the test, the samples would burn loose from their suspension means and tumble.

The ignited samples flamed brightly as they tumbled in the empty drum. The infrared sensor recorded temperatures approaching 300 °C in the drum whenever the sample passed into the sensor's field of view. Figure 31 shows the infrared sensor's response. There was a slight rise in the air temperature at the entrance to the blower. The maximum recorded air temperature at the blower intake was about 50 °C. By the time the air reached the exhaust duct, the air had cooled to around 38 °C.

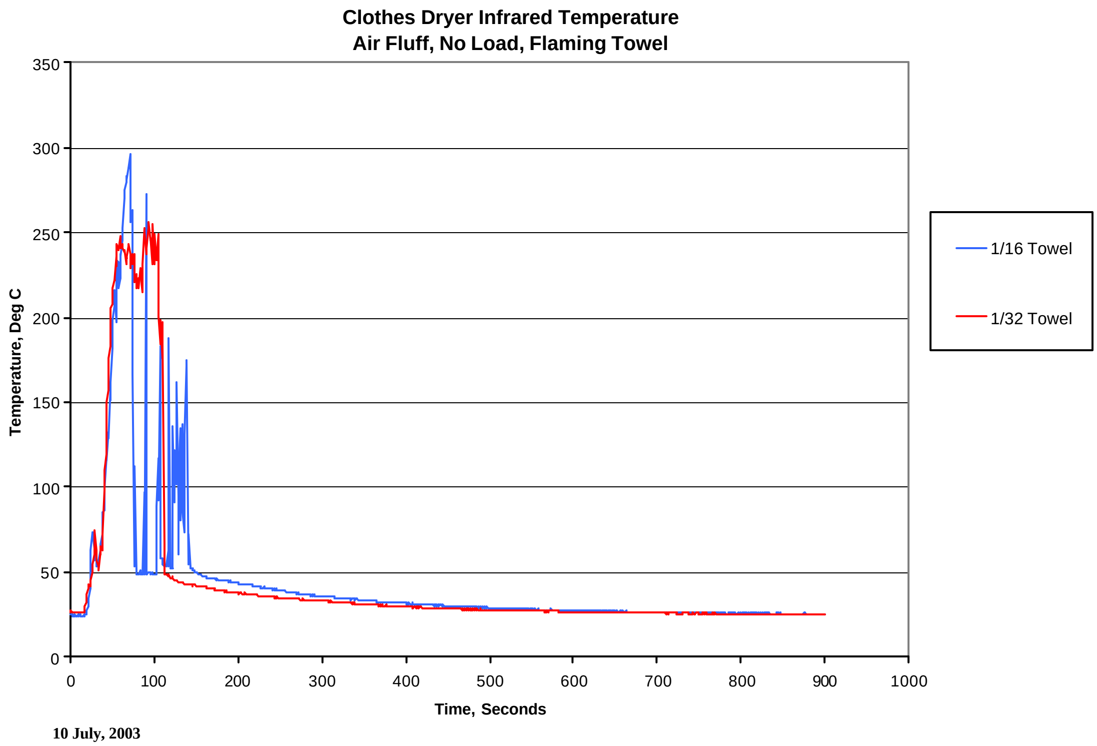


Figure 31. Infrared Sensor Response to Flaming Combustion

Flaming combustion generated strong signals on all the gas sensors in the exhaust duct. The 1/16th towel sample saturated the carbon dioxide sensor output at 5000 PPM. With the blower operating and no towel load to restrict the airflow, there was less carbon monoxide produced; but the peak measured levels were still 10 to 17 times the background reading. The VOC sensor also detected the combustion with a doubling of its output reading. Figures 32 through 34 show the gas sensor responses to flaming combustion in the tumbler.

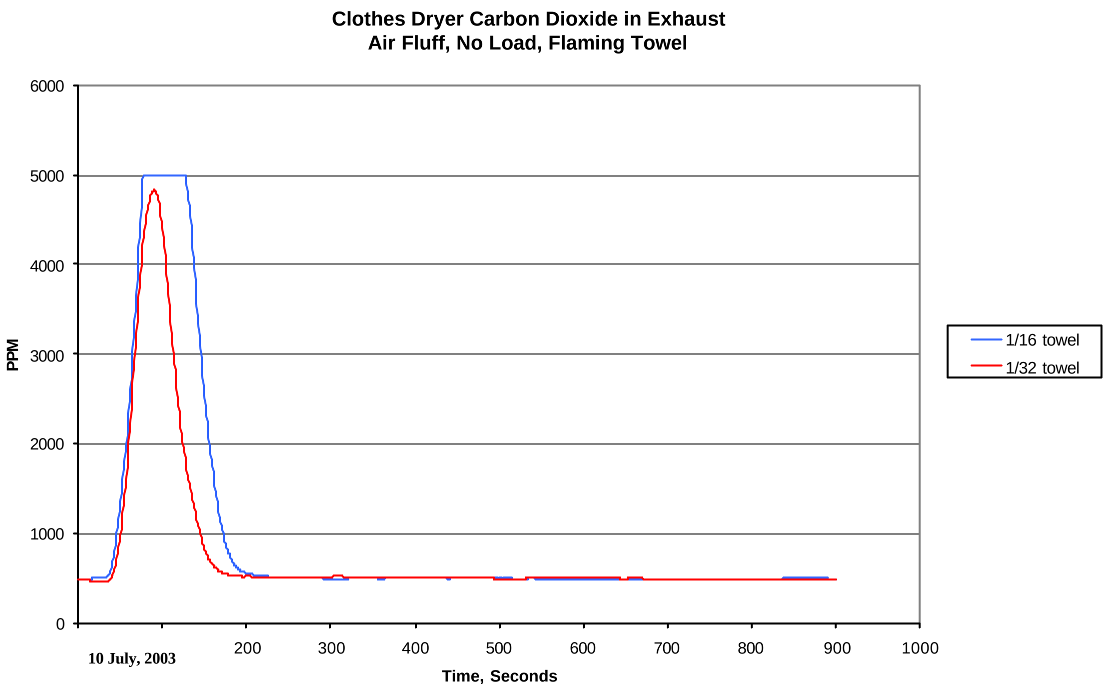


Figure 32. Carbon Dioxide Sensor Response to Flaming Combustion

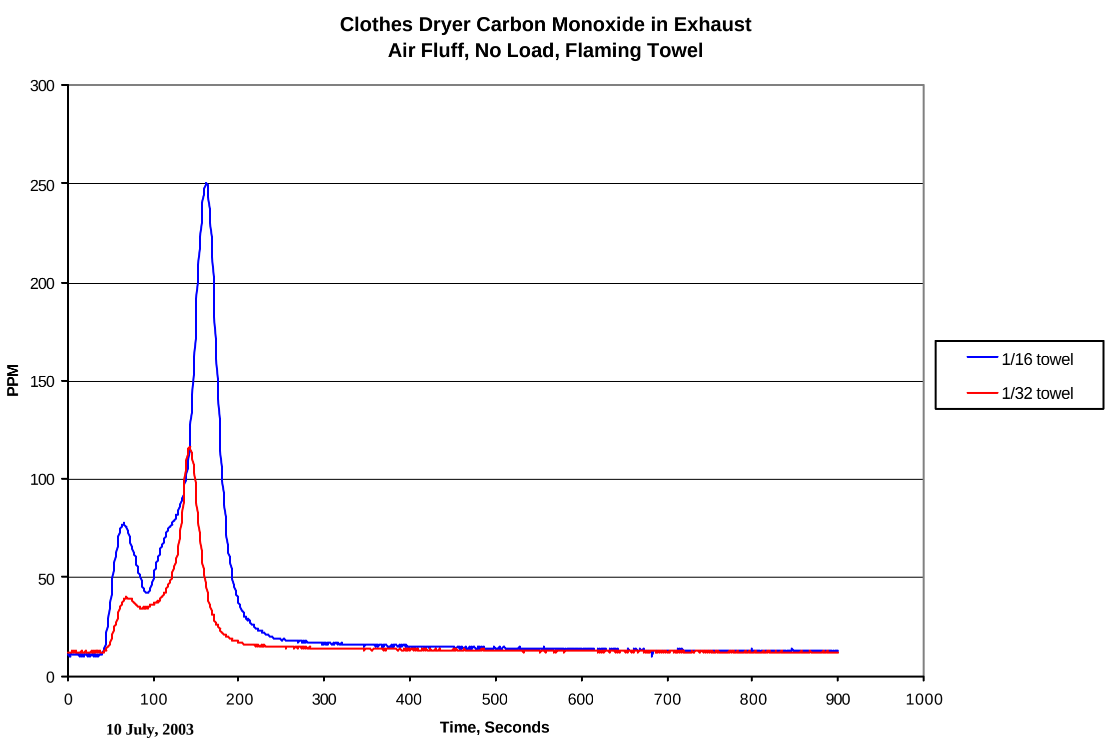


Figure 33. Carbon Monoxide Sensor Response to Flaming Combustion

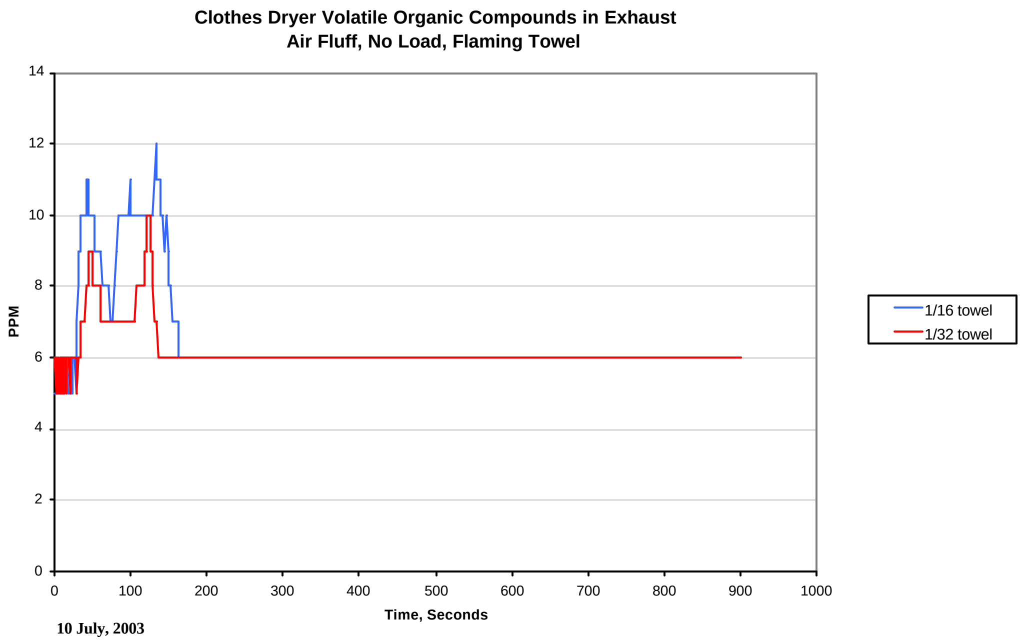


Figure 34. VOC Sensor Response to Flaming Combustion

4.12 Spontaneous Combustion

Three tests were conducted to assess the ability to detect the early stages of spontaneous combustion with sensors. In two of the tests, 100% soybean oil was used on separate towel sets. The third test used boiled linseed oil.

For these sets of tests, the CO, CO_2, and VOC sensors were relocated from the exhaust ducting to the interior of the drum. The dryer door was removed and a clear panel was secured in its place. The three sensors were mounted on the upper portion of the clear panel, as shown in Figure 35. A thermocouple was inserted into the load to monitor the temperature inside the load after it had stopped tumbling.

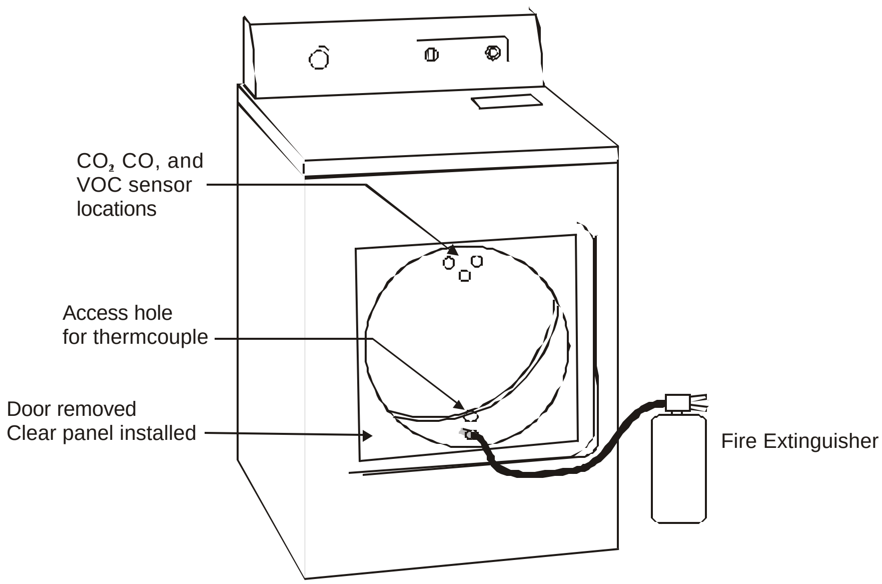


Figure 35. Test Setup for Spontaneous Combustion

For the first test with soybean oil, 50% of the dry towel load's weight in oil (about 5 pounds of oil, or 2.3 kg) was added to a load of 9 towels. The 9 towels were then washed with a standard detergent (AATCC 1993 Standard Reference Detergent). One towel was removed after washing and for chemical analysis to determine the residual oil in the towel. The remaining 8 towels were placed in the dryer and dried at the high heat setting for approximately 120 minutes. The dryer was stopped before the cool-down cycle, and a thermocouple on a stiff rod was inserted into the load. The sensor outputs were monitored during the period after drying as the load sat in the tumbler.

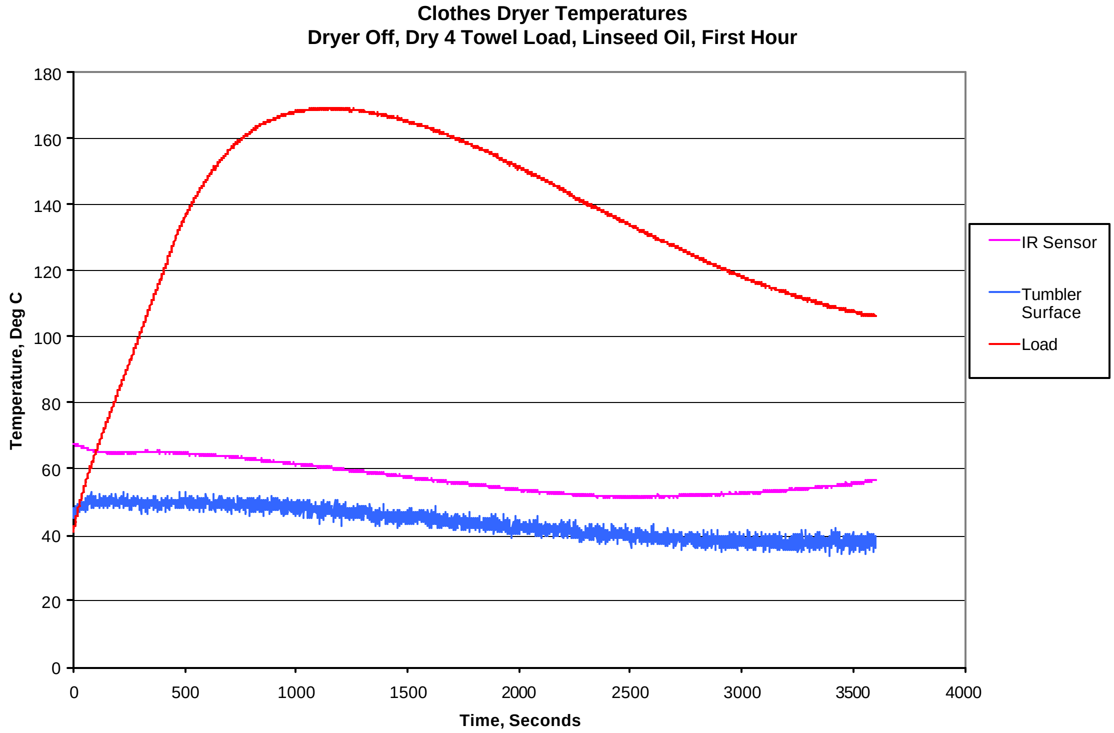
Laboratory analysis of the towels showed a residual oil concentration of 0.025 g/in^2 on the towel tested. Using a value of 26.4 g/oz. for vegetable oil and a towel area of 1193 $inches^2$ for a towel, the remaining volume of oil in the towel load was calculated as approximately 9 fluid ounces.

During the 2-hour period after drying, there were no indications of conditions that might lead to a spontaneous combustion situation. The air and clothing load temperatures in the tumbler and the rest of the clothes dryer smoothly decreased from around 70 °C to about 36 °C over the next hour. There were no recorded levels of CO or VOC above their background levels. Measured carbon dioxide levels in the drum rose and fell between a low of 270 PPM and a high of 420 PPM.

For the second test, a set of 8 dry towels was used. An amount of oil equal to 25% of the towels' weight (2.3 lbs., or 1.04 kg) was added to the towels. The oiled towels were loaded into the dryer and dried on the high heat setting until the control thermostat began cycling and the exhaust air temperature had stabilized (approximately 15 minutes). The dryer was stopped before the cool-down cycle, and the sensors were monitored for 2 hours. Again, over a 2-hour period, the air temperatures in the tumbler and elsewhere smoothly decreased from 79 °C towards 25 °C. The temperature of the load decreased from 73 °C to about 54 °C. There were no changes in the levels of CO or VOC. The amount of CO_2 in the tumbler quickly increased from about 550 PPM to 650 PPM in the first twenty seconds of data recording. After that peak, the CO_2 level dropped smoothly to around 500 PPM over the next 15 minutes. No further changes in the concentration of CO_2 were noticed.

For the third test, 4 towels (½ of a towel set) had 25% of their weight (1.2 lbs., or 556 g) of boiled linseed oil added. This half-set was dried for approximately 15 minutes. As before, a temperature sensor was inserted into the load through the door, and CO_2, CO, and VOC in the tumbler were monitored. Immediately after stopping the clothes dryer (without a cool-down cycle), the levels of CO_2, CO and VOC all increased rapidly. After 4 minutes, the CO detector had reached its maximum reading of 2000 PPM. About 8 minutes after stopping the clothes dryer, the VOC sensor read a maximum level of 136 PPM. After 10 minutes, the CO_2 detector had reached its maximum reading of 5000 PPM. These gas levels did not decrease from their maximums until after the test had concluded and the clothes dryer was run on the air fluff cycle to exhaust the tumbler.

Most of the temperatures monitored in the clothes dryer decreased smoothly towards an asymptotic value of around 40 °C. However, the temperature sensor inserted into the load rose from 45 °C to 169 °C over an 18-minute period before starting to decrease. The sensor did not reach the center of the load and, therefore, probably did not measure the hottest area. Figure 36 shows some measured temperatures over the first hour after the dryer was stopped.



23 July, 2003

Figure 36. Linseed Oil and Towels in the Drum During the First 60 Minutes

Thirty minutes after the dryer had been stopped, smoke could be seen leaking from the clothes dryer. The amount of smoke increased steadily during the testing. After 50 minutes, the inner rear wall of the tumbler was difficult to see through the smoke in the dryer. At about the 70-minute mark, the load temperature started to rise from a minimum of 100 °C. The infrared temperature sensor output increased due to emission from the portion of the load in the sensor's field of view.

The test was terminated at the 100-minute mark. By this time, the load temperature had risen to 143 °C, and the infrared sensor output was at 81 °C. The clothes dryer was emitting large amounts of thick smoke. The dryer was started on the air fluff cycle to determine if the load could be cooled by tumbling. The dryer load quickly ignited once fresh air was introduced into the tumbler, as shown in Figure 37 by the sudden increase in the infrared and blower intake temperatures. (The sudden decrease in temperature was caused by the release of CO_2 from the fire extinguisher.)

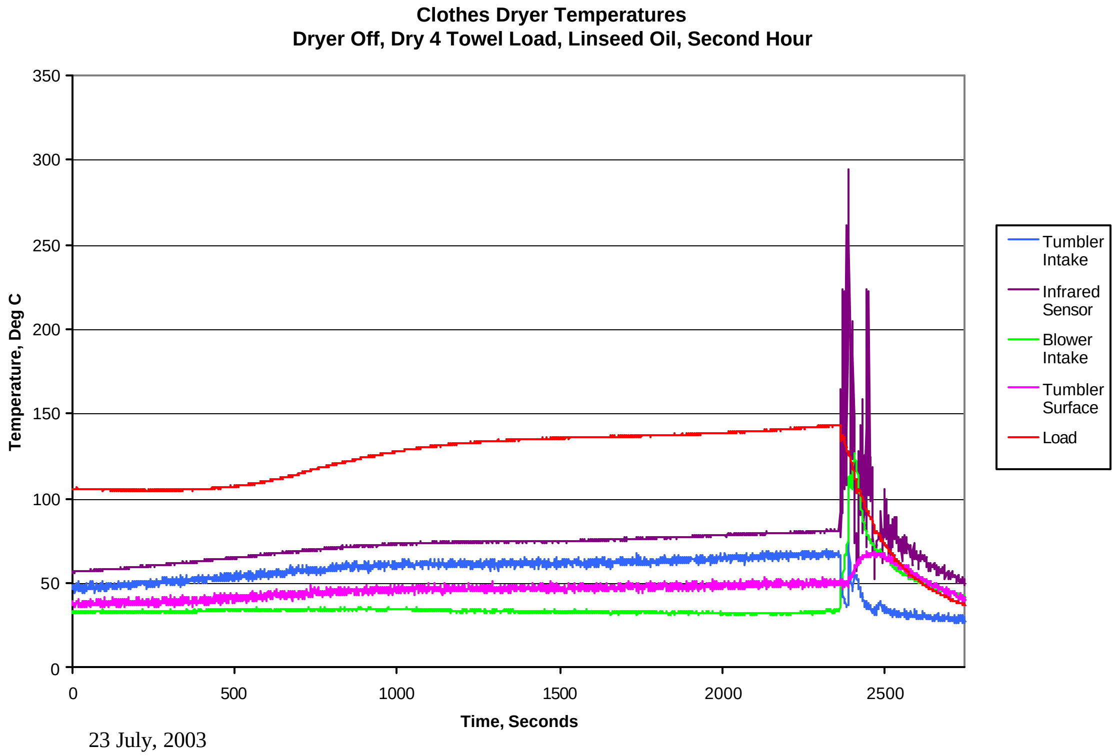


Figure 37. Linseed Oil and Towels in the Drum for the Second 60 Minutes

5.0 DETECTION OF TEST CONDITIONS

Each of the test conditions investigated was detectable through the sensor responses generated. The single condition that did not change the sensor outputs from their typical responses was 25% blockage of the exhaust vent. In some experiments, the test condition was detectable by an increase in a sensor reading. In other experiments, reduced sensor output (airflow with a blocked exhaust vent, for example) identified a particular test condition. Strong sensor responses were obtained in some tests, while other test conditions only generated a weak change in a sensor output.

Table 2 summarizes the response of each sensor to the conditions tested. In the table, a higher value indicates a stronger sensor response compared to normal values. A negative value indicates a decrease in the sensor reading as a result of the test condition.

Table 2. Relative Sensor Response to Test Conditions

	SENSOR												
	Cycling	Temperature			Exhaust Gases								
	Hi Limit Thermostat	Infrared Sensor	Tumbler Intake	Control Thermostat	VOC	CO	CO2	RH	Motor Current	RPM	Pressure Sensor	Accelero-meter	Airflow
TEST CONDITION													
smoldering combustion					2	3	1						
flaming combustion		3			3	3	3						
spontaneous combustion		2			3	3	3						
detection of VOC					3								
electric heat coil partial short	2		2	2					3				
overfilled drum										1			-1
missing lint screen	2		2	2				2			-1		2
blocked lint screen (100%)	3		3	3							3		-1
blocked lint screen (75%)											3		-1
blocked lint screen (50%)											3		
blocked lint screen (25%)											3		
blocked exhaust path (100%)	3		3	3									-3
blocked exhaust path (75%)	2		2	2									-2
blocked exhaust path (50%)													-2
blocked exhaust path (25%)													
air leak blower intake			1	1									1
air leak exhaust duct								-1					-1
air leak ducting behind drum			2								1		1
air leak drum gasket			2	-2									1

Sensor Response: 3 = Much stronger response than normal case; -3 = Much weaker response than normal case
2 = Stronger response than normal case; -2 = Weaker response than normal case
1 = Slightly stronger response than normal case; -1 = Slightly weaker response than normal case

5.1 Combustion

For smoldering, flaming, or spontaneous combustion, the exhaust gas detectors usually generated redundant, strong responses. The CO_2 response to smoldering combustion was not easily discernible due to the normal atmospheric levels of carbon dioxide and their normal variations in concentration. Carbon monoxide appears to be a more robust indicator than carbon dioxide or VOC due to its low background level and the magnitude of its response. The infrared sensor output was capable of distinguishing smoldering combustion from flaming and spontaneous combustion.

5.2 Temperature

Temperatures throughout the clothes dryer generally displayed one of three characteristic patterns:

1. The first pattern involves sensors in areas outside the airflow system (control panel, chassis interior). These sensors responded weakly to test conditions, usually reporting a fixed offset from the ambient air temperature throughout the drying cycle.

2. The second observed pattern includes sensors in the airflow path (blower intake and exhaust, exhaust duct, tumbler surface, IR sensor). These sensors tended to track together as a group, rising and falling in temperature in response to the activation of the control thermostat.

3. The third pattern involves the sensors next to the heating element (heater intake and tumbler intake). The responses from these sensors also rose and fell in response to heating element cycling, but at much higher peak temperatures and with larger temperature swings between the high and low readings. Reviewing Table 2 shows that only the air leak conditions after the tumbler and inside the dryer resulted in a dissimilar response between the tumbler intake air temperature and other measured temperatures. This is because air leaks tend to cool the air downstream of the leak and heat the air upstream of the leak (due to constant heating element power dissipation and reduced airflow).

The air temperature at the tumbler intake can also be assessed by a means other than a temperature-sensitive device. Cycling of the high limit thermostat is indicative of high air temperatures near the heating element. Monitoring the high limit thermostat response could be used to detect several of the test conditions.

5.3 Airflow

Airflow in the exhaust duct responded to more test conditions than any other sensor. Often the change was a decrease in flow through the duct. Also, many test conditions elicited only a small magnitude change in the airflow.

5.4 Sensors with Weak Responses

Some of the sensors did not appreciably change their outputs based on any of the test conditions. The accelerometers on the motor mount reliably detected motor shaft rotation but had only a weak response to the presence of a load in the tumbler. In the FFT data analyses, only small changes at frequencies below 1 Hz indicated that the tumbler was not empty. The accelerometer data could not reliably be used to determine if the load was wet or dry. The exhaust relative humidity readings had the widest dynamic range during a drying cycle, but the sensor was ineffective at discriminating between ordinary operation and most test conditions. Likewise, very large changes in the towel load were only weakly reflected in the output of the drum rotation sensor.

5.5 Sensor Fusion for Condition Detection

Sensor fusion is the combination of signals from different types of sensors to determine an operating state. An analysis of the data presented in Table 2 shows that, for some test conditions, combinations of different sensor readings are needed to more precisely identify the condition. More than one combination is possible for some of the tested conditions. Table 3 details some of the sensor combinations.

Usually, two sensors can identify a particular test condition. Three sensors are required to distinguish a missing lint screen from a general air leak. For some test conditions (smoldering combustion, heating element partial short-circuit, overfilled drum), the absence of a change from normal is the distinguishing characteristic of a sensor's response.

Table 3. Sensor Combinations to Detect Tested Conditions

TEST CONDITION	**a) SENSOR TYPE** **b) LOCATION** **c) RESPONSE**		
General Air Leak	a) Air Temperature b) Tumbler Intake c) High	a) Airflow b) Exhaust Duct c) Increase	
Ducting Behind Drum Air Leak	a) Air Temperature b) Tumbler Intake c) High	a) Airflow b) Exhaust Duct c) Increase	a) Relative Humidity b) Exhaust Duct c) Decrease Change
Exhaust Duct Blockage	a) Air Temperature b) Tumbler Intake c) High	a) Airflow b) Exhaust Duct c) Decrease	
Flaming or Spontaneous Combustion	a) Carbon Monoxide b) Exhaust Duct c) Increase	a) Infrared Radiation b) Tumbler c) Increase	
Smoldering Combustion	a) Carbon Monoxide b) Exhaust Duct c) Increase	a) Infrared Radiation b) Tumbler c) No Change	
Presence of VOC	a) VOC b) Exhaust Duct c) Increase		
Blocked Lint Screen	a) Air Temperature b) Tumbler Intake c) High	a) Static Pressure b) Lint Screen c) Increase	
Missing Lint Screen	a) Air Temperature b) Tumbler Intake c) High	a) Airflow b) Exhaust Duct c) Increase	a) Static Pressure b) Lint Screen c) Decrease
Heating Element Coil Partial Short-Circuit	a) Air Temperature b) Tumbler Intake c) High	a) Airflow b) Exhaust Duct c) No Change	a) Current b) Heating Element c) Increase
Overfilled Drum	a) Air Temperature b) Multiple Sites c) No Change	a) Rotation Rate b) Tumbler c) Decrease	a) Airflow b) Exhaust Duct c) Decrease (Some dryer designs)

Sensor Response: High = Greater amplitude than the normal response
No Change = Amplitude equal to the normal response
Increase = Amplitude above the normal response
Decrease = Amplitude below the normal response
Decrease Change = Change from start to finish is less than the normal response

5.6 Example Sensor Fusion Combinations

If a subset of the sensors tested is arbitrarily chosen, the concepts of sensor fusion can be demonstrated. By itself, a sensor output outside of its typical range can be ambiguous. When combined with other sensor outputs the particular operating state of the clothes dryer can be determined more accurately.

Table 4 shows the responses of three selected sensors to the test conditions. This selection includes temperature, pressure, and airflow. Logical inferences can be made between the combination of sensor responses and the functional condition of the clothes dryer. Algorithms using the logical AND, OR, and NOT operators can be combined with sensor readings (e.g., typical, higher than typical, lower than typical) in a truth table format to identify particular clothes dryer operating states. Figures 38 through 44 provide a visual explanation of sensor fusion in operation. A normal sensor response is depicted as having the dial pointer in the green area of the dial indicator. An abnormal response, either higher or lower than the expected range is shown as the dial pointer in a yellow area. The sensor outputs are considered in their combination to define the particular test condition.

Table 4. Three Sensors' Response to Test Conditions

	Tumbler Intake	**Pressure Sensor**	**Exhaust Airflow**
TEST CONDITION			
electric heat coil partial short	2		
overfilled drum			-1
missing lint screen	2	-1	2
blocked lint screen (100%)	3	3	-1
blocked lint screen (75%)		3	-1
blocked lint screen (50%)		3	
blocked lint screen (25%)		3	
blocked exhaust path (100%)	3		-3
blocked exhaust path (75%)	2		-2
blocked exhaust path (50%)			-2
air leak blower intake	1		1
air leak exhaust duct			-1
air leak ducting behind drum	2	1	1
air leak drum gasket	2		1

Sensor Response:
3 = Much stronger response than normal case; -3 = Much weaker response than normal case
2 = Stronger response than normal case; -2 = Weaker response than normal case
1 = Slightly stronger response than normal case; -1 = Slightly weaker response than normal case

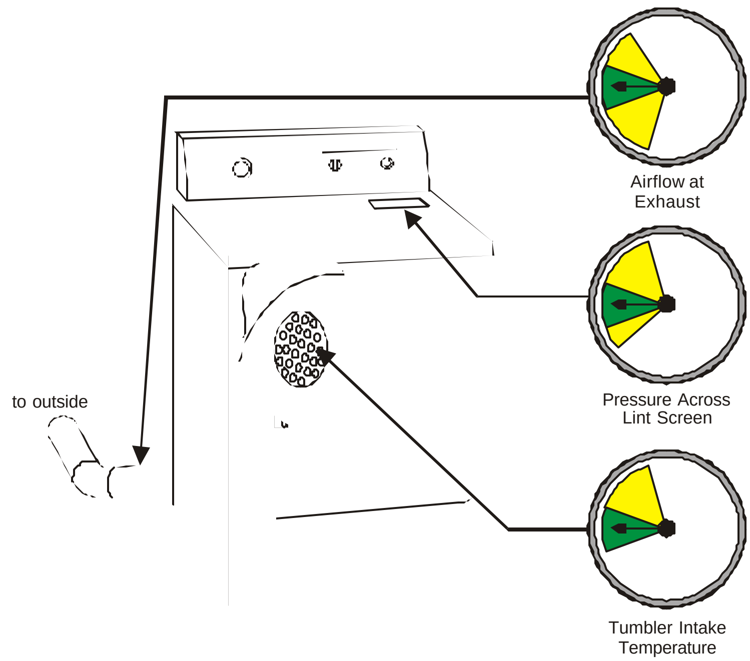


Figure 38. Sensors indicating Normal Operation

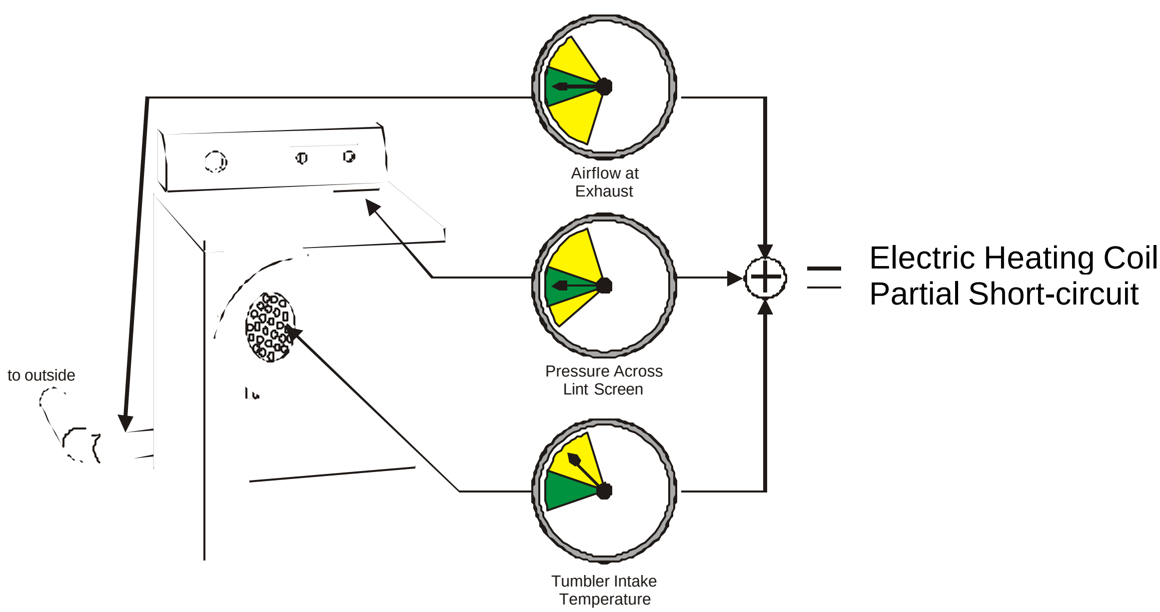


Figure 39. Sensors indicating Electric Heating Coil Partial Short-Circuit

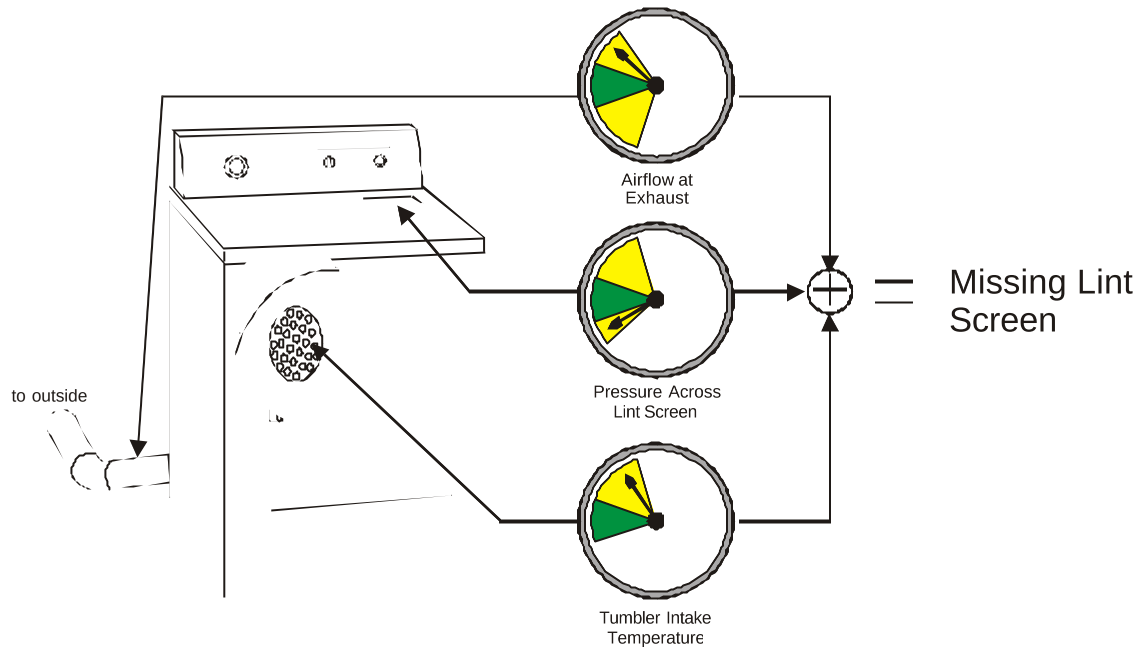


Figure 40. Sensors indicating Missing Lint Screen

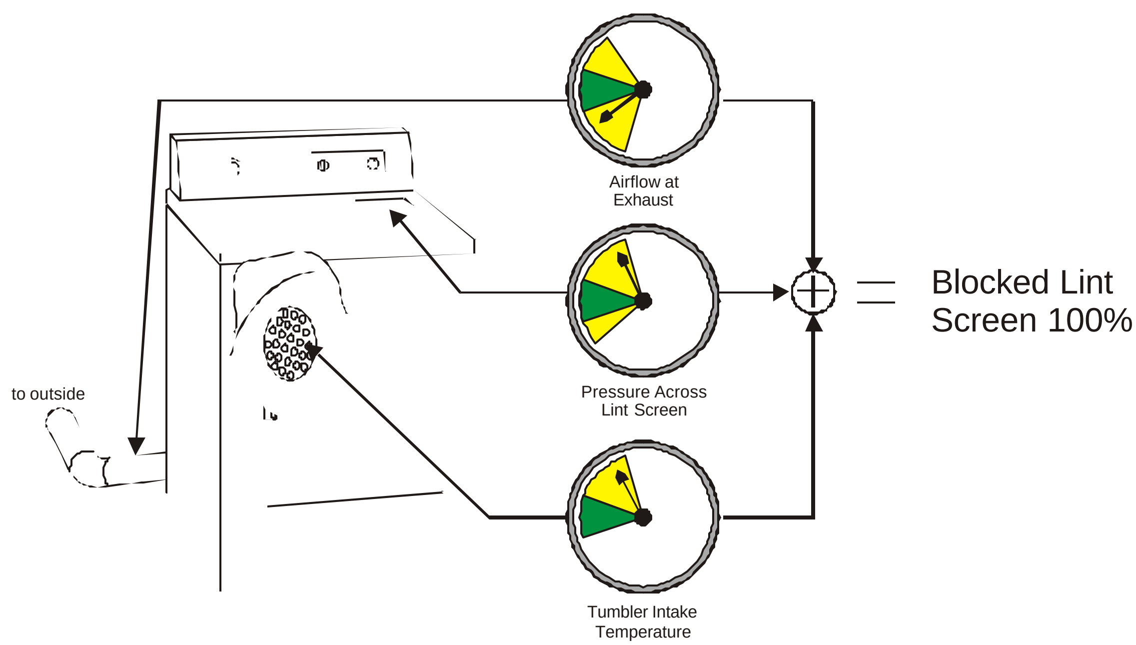


Figure 41. Sensors indicating Blocked Lint Screen

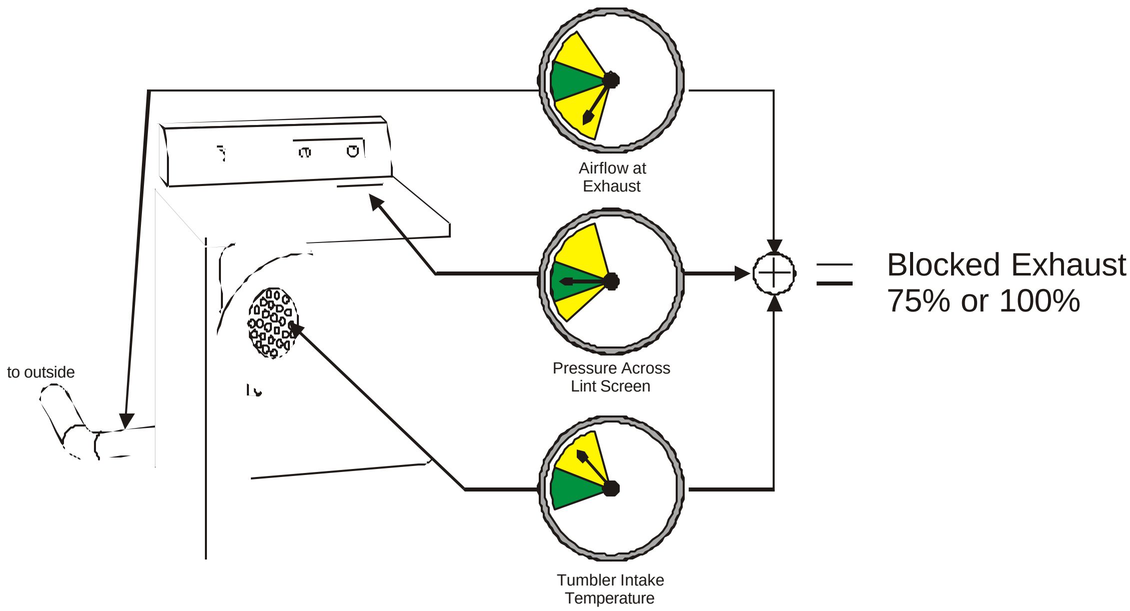


Figure 42. Sensors indicating Blocked Exhaust

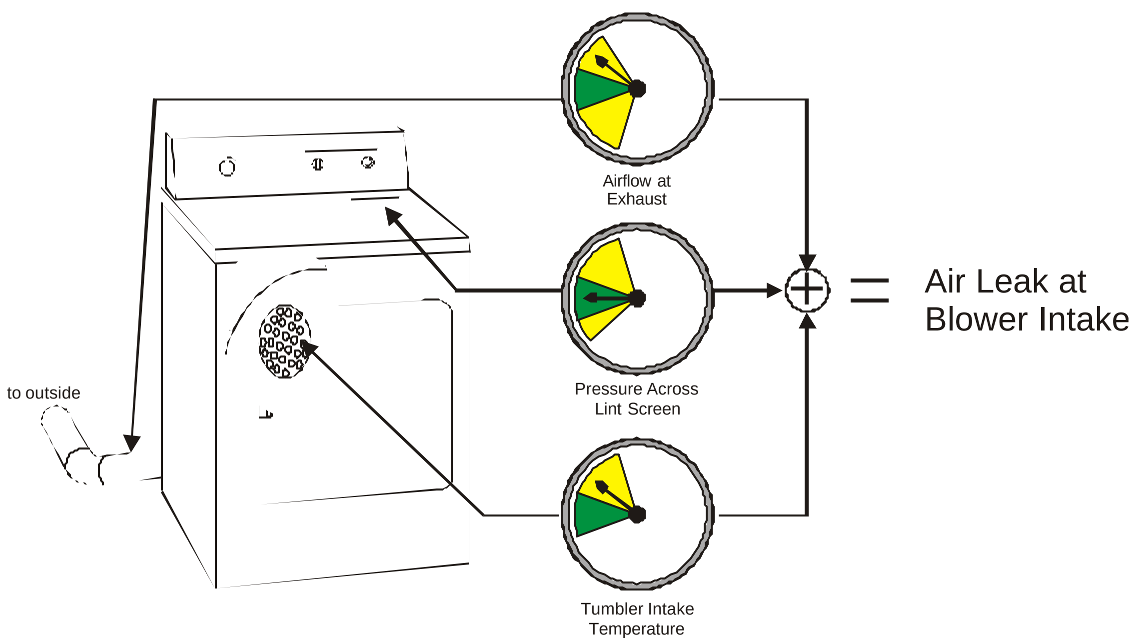


Figure 43. Sensors indicating Air Leak at Blower Intake

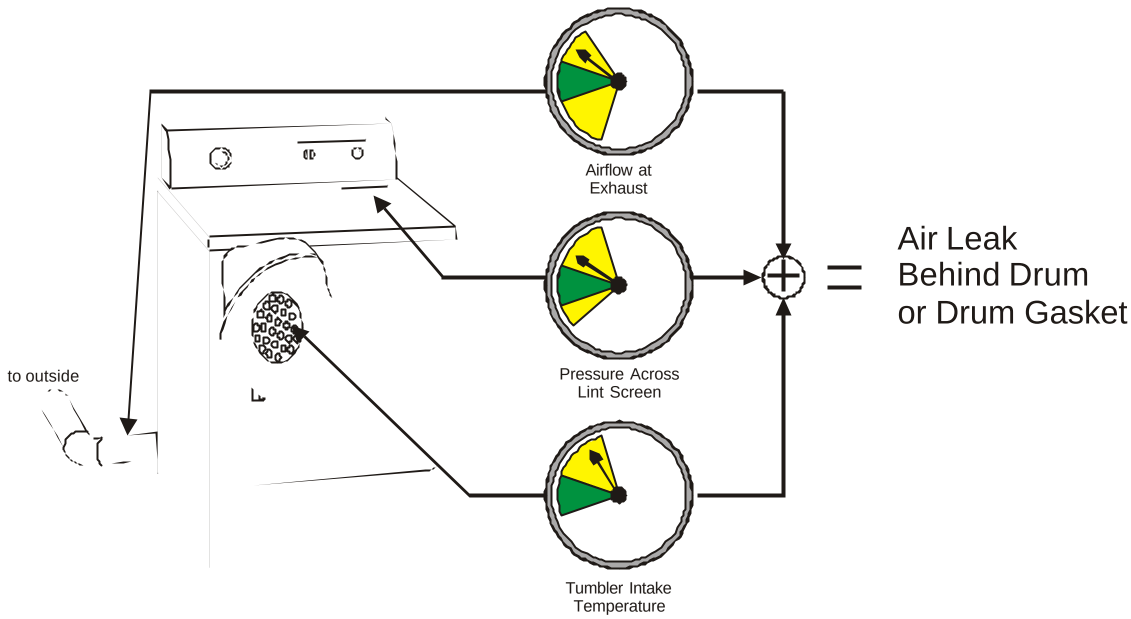


Figure 44. Sensors indicating Air Leak Behind Drum or Drum Gasket

5.7 Condition-Based Monitoring of Exhaust Airflow

The magnitude of the airflow in the exhaust duct is dependent on the clothes dryer installation and the exhaust path. Further, the response of airflow to many of the tested conditions is relatively small compared to its average condition (about 1340 fpm). In order to discriminate normal from abnormal clothes dryer operation using the exhaust airflow as a sensed variable, precise flow determinations are required. One way to meet this requirement without prior knowledge of the installation and ducting characteristics is through condition-based monitoring.

With condition-based monitoring, the "normal" airflow of a clothes dryer as installed is established. One way to derive a "normal" airflow value is for measurements from the first *N* dryer loads to be averaged. Another technique could be to operate the dryer with conditions associated with high airflow and low airflow and develop a "normal" value based on the results. Other methodologies are also available.

With the normal value established, two operations are conducted as the dryer is used. First, each time the dryer is operated, an airflow value is determined for that use. The new value is compared to the "normal" value to determine if the difference between the two is significant. If so, other clothes dryer sensors could be polled to help determine if the variation in airflow is indicative of a potential hazard. Second, multiple dryer load airflow calculations could be evaluated together to determine if any long-term changes in dryer operation are occurring. For example, a gradual blocking of the exhaust vent over a long period of time would be detected as a slow change in the calculated airflow (a type of "mean shift"). The normal airflow could be updated from time to time (e.g., always use the last *M* dryer runs to calculate the normal value) for use in evaluating the performance of the last load dried. The installation value could be retained for comparison to the latest calculated normal value to ascertain slow changes. Other techniques could be employed as well. With this system, long-term degradation and sudden component failures could be detected.

Through the use of condition-based monitoring, it is possible that small changes and long-term changes can be distinguished from the turbulent airflow in the exhaust duct.

5.8 Limitations of the Testing

The results from these tests are not immediately applicable to production clothes dryers. The following factors must be considered when using the data from these experiments.

5.8.1 Dryer Type

Only one design of clothes dryer was used in the testing. The airflow through the tumbler, the locations of the thermostats, and the form of the lint screen are likely to have a significant effect on the sensor readings.

5.8.2 Load Type

Only one type of dryer load, 8 cotton towels, was used for most of the testing. Other types of fabrics in different amounts are likely to affect the operation of the dryer in terms of airflow and temperatures.

5.8.3 Repetitions

Many of the tests conducted with the clothes dryer were repetitions of previously run experiments. As mentioned earlier, 35 normal operating tests were conducted. However, for most of the test conditions, insufficient repetitions were conducted to precisely determine normal variability of sensor outputs for that test.

5.8.4 Test Conditions

Nineteen different non-normal test conditions were evaluated during the experimental phase of this project. This set does not represent all the potential operating conditions that can exist in a clothes dryer. Also, combinations of test conditions were not evaluated.

5.8.5 Long-Term Effects

The testing conducted on the clothes dryer did not cover a sufficient length of time or run a large enough number of loads to determine how the device operates over the long term. If a value of 500 cycles per year is used as the average use of a clothes dryer in the U.S., the testing in this project represents about 27% of one year's use. The clothes dryer used in this project was purchased new in 2002. Variations in clothes dryer operation caused by use or age were not evaluated by these experiments.

6.0 CONCLUSIONS

Twenty-three sensors were installed in an electric clothes dryer. During normal and abnormal operation, sensor outputs were recorded and analyzed. The testing showed some of the possibilities for detection of non-normal clothes dryer operation.

6.1 Abnormal Operation Detection

Each of the nine defined abnormal test conditions was uniquely identifiable by examining the sensor outputs. From one to three sensors were required to identify a particular test condition. Discrimination of normal from abnormal testing conditions usually depended on discerning a change from previously established typical values. Depending on the amount of "abnormality" in the testing parameters, the sensor response changes were small or large.

6.2 Sensor Fusion

This set of experiments showed that it is possible to use sensor fusion for detecting abnormal clothes dryer operation. For most of the abnormal tests, multiple sensors of different types are required to identify the specific conditions in the clothes dryer. In these tests, multiple combinations of sensor outputs were capable of identifying a particular test condition. Clothes dryer product designers could use this flexibility in formulating new systems with wider fault coverage.

6.3 Condition-Based Monitoring

For small magnitude or long-term changes, condition-based monitoring is one technique with the potential of generating useful information on the state of clothes dryer operation. The exhaust airflow variable is sensitive to many types of abnormal operation. However, in many cases, the amplitude of the change from normal conditions is small. Also, the test parameters represent conditions that may take a very long time to build up so that each successive dryer use only marginally changes the sensor output from its previous value. Condition-based monitoring holds the possibility that a control system in a clothes dryer may be able to discern these hard-to-detect conditions.

6.4 One Potential Sensor System

By examining Tables 2 and 3, a subset of the sensors used could be defined that provides some detection ability for the abnormal test conditions. If the tumbler intake temperature (or alternatively, activation of the high limit thermostat) and the exhaust airflow are observed during operation, the following test conditions could be detected:

- Electric heating coil partial short-circuit
- Overfilled drum
- Missing lint screen
- Blocked lint screen
- Blocked exhaust duct
- Air leak

With these two sensors, not every condition can be discriminated, but a control system would be aware of operation outside of normal conditions. If a CO sensor is added to the system, the following additional test conditions can be detected:

- Smoldering combustion
- Flaming combustion
- Spontaneous combustion

The VOC and CO sensors responded similarly when exposed to combustion conditions. In addition, the VOC sensor includes sensitivity to the presence of unburned volatile organic compounds. The VOC sensor used in this project responded weakly to many test conditions. A different sensor, or one specialized to clothes dryer operation, may prove to be adequate for both combustion product and VOC chemical detection.

If the output from the differential pressure sensor is added to the system, a greater sensitivity to lint screen blockage and some air leaks can be achieved. With the pressure sensor, a response of no change from typical operation can be combined with other sensor outputs to discriminate blocked exhaust duct conditions from blocked lint screen conditions.

6.5 Potential for Future Testing/Development

The testing on this electric clothes dryer shows some of the potential of using sensors in appliances to reduce potential fire hazards. More research would be needed to characterize and optimize the performance of any sensors selected for a system design. Listed below are some additional research possibilities that could be pursued.

6.5.1 Sensor Reposition

Only one location for each sensor was tested. Other positions may offer a stronger response, higher sensitivity, or wider dynamic range than the one selected.

The airflow sensor might be repositioned into the clothes dryer body, perhaps in the ducting from the tumbler to the blower. This has the highest airflow at the lowest average pressure of the clothes dryer airflow pathway.

The accelerometers detected motor shaft rotation very well but were relatively insensitive to drum vibrations. Repositioning the sensors to the stationary rear wall of the tumbler may provide more information on the clothing load.

The Hall Effect sensor and the 32 magnets gave a relatively low-resolution look at drum rotation. The use of a toothed flange on the drum or an optical sensor/encoder system holds the promise of producing rotation data with much finer resolution. Within-revolution events could be distinguished easily with such a sensor system.

6.5.2 Investigate Alternate Dryer Designs

Flow-through dryer designs, with the lint screen in the clothes dryer door, are likely to have different airflow, pressure, and temperature responses to the test conditions. Those responses have not been quantified. Which sensors are best for detection and discrimination of the test conditions is unknown.

6.5.3 Evaluate Other Abnormal Conditions

Other operating conditions or combinations of conditions can be investigated to see if the sensor system can adequately respond. For example, a lint screen with a hole in the mesh was not part of the testing program. The sensor responses to combinations of test conditions may not add linearly and cannot be predicted beforehand.

6.5.4 Vary the Clothes Dryer Load

Changing the size of the load and its fabric content will help identify the range of sensor responses that should be considered "normal." The effects of temperature and airflow changes on synthetic fibers may or may not be significant.

6.5.5 Evaluate the Effects of Ambient Environment

The tests conducted in this project did not span the expected range of ambient environmental factors. Understanding the impact of altitude, air temperature, and ambient humidity on sensor responses will help determine how much information a sensor system needs from the clothes dryer's environment for proper abnormal operation detection.

6.5.6 Develop Sensor Algorithms

Ultimately, the data generated by any sensor system will require analysis in order to determine whether an incipient hazard condition exists and what actions should be taken. The design of algorithms to interpret sensor data could help define the types of sensors needed and what accuracy and precision are required. Effects such as appliance age, maintenance, environment, and usage patterns would need to be accounted for in algorithm design.

Appendix A: Derivation of Abnormal Testing Conditions

The National Fire Protection Association (NFPA) report, *The U.S. Home Product Report (Appliances and Equipment involved in Fires), January 2002*, and CPSC's In-depth Investigation (IDI) reports were examined to gain insight into which "abnormal" test conditions should be evaluated.

The NFPA report provided information on the ignition factors and first material ignited in reported clothes dryer fires. Table 1 lists the ignition factor for clothes dryer fires for U.S. homes, 1994-1998 annual average. Lack of maintenance was the leading ignition factor at 29.5% of total fires. The next three ignition factors each had approximately 10% of the total fires - Unclassified or unknown-type of mechanical failure; part failure, leak or break; and short circuit or ground fault.

Table 1. Ignition Factor*

Ignition Factor	**Fires**	
	Number	**Percentage**
Lack of maintenance	4,400	29.5
Unclassifies or unknown-type mechanical failure	1,600	10.8
Part failure, leak, or break	1,400	9.8
Short circuit or ground fault	1,400	9.7
Combustible too close	1,200	8.0
Unclassified or unknown-type operational deficiency	1,000	7.0
Electrical failure other than short circuit	800	5.4
Automatic control failure	600	3.8
Overloaded	400	2.7
Unattended	300	2.0
Unclassified ignition factor	300	1.9
Spontaneous heating	300	1.8
Other installation deficiency	200	1.3
Other known	900	6.2
Total	**14,800**	**100.0**

*Table from *The U.S. Home Product Report*, January 2002, Clothes Dryer Fires in U.S. Homes, 1994-1998 Annual Average, Unknowns Allocated, page 81

For the ignition factor, lack of maintenance, the report does not specify what lack of maintenance would encompass, but it can be speculated that lack of maintenance could include the following:

- Not cleaning the lint screen
- Not cleaning the lint or dust around the dryer
- Not cleaning the lint or duct inside the dryer chassis
- Not cleaning the lint from the exhaust duct

Table 2 lists the form of material first ignited for clothes dryer fires in U.S. homes, 1994-1998 annual average. The NFPA report states that clothing not on a person was the leading material first ignited in 32% of total fires, followed closely by dust, fiber or lint at 27.7%. The third leading material was wire or cable insulation at 8.1%.

Table 2. Form of Material First Ignited*

Ignition Factor	**Fires**	
	Number	**Percentage**
Clothing not on a person	4,700	32.0
Duct, fiber or lint	4,100	27.7
Wire or cable insulation	1,200	8.1
Linen other than bedding	700	5.0
Unclassified or unknown -type soft goods	700	4.9
Unclassified form of material	500	3.4
Interior wall covering	300	2.2
Trash	300	2.2
Mattress or bedding	300	2.2
Multiple forms of material	300	2.1
Appliance housing or casing	200	1.7
Clothing on a person	200	1.1
Structural member or framing	100	1.0
Other known	1,000	6.6
Total	**14,800**	**100.0**

*Table from *The U.S. Home Product Report*, January 2002, Clothes Dryer Fires in U.S. Homes, 1994-1998 Annual Average, Unknowns Allocated, page 82

To supplement the information from the NFPA report, CPSC staff reviewed In-depth Investigations (IDIs) of clothes dryer fire incidents conducted from 1993 to 2000. IDIs contain summaries of reports of investigations into events surrounding product-related injuries or incidents. Based on victim/witness interviews and examination of the incident product, the reports may provide details about incident sequence, human behavior, and product involvement.

Two hundred ninety-three IDIs were reviewed. Of those, 139 IDIs were considered out of scope or did not state what the possible cause for the fire involving a clothes dryer. The remaining 154 IDIs could be classified into one of the known categories listed in Table 1 of this appendix.

IDIs in which dryer fire incidents involved lint, dust or fibers were reviewed. Incidents of lint ignition inside the dryer included areas near the heater, dryer base, lint screen, and motor. Outside the dryer, areas behind the clothes dryer and in the home exhaust duct were mentioned as areas where lint ignited. The sizes of the fires reported ranged from small ones that self-extinguished to extensive fires that spread to surrounding combustibles near the dryer. Lint build-up in the exhaust duct or on the lint screen was mentioned as a possible cause for the dryer fire incidents.

IDIs in which dryer fire incidents involved overloading the tumbler were reviewed. Large items such as comforters, blankets, pillows, or cushions were being dried in a clothes dryer when either scorching or a fire occurred.

An IDI in which a clothes dryer fire incident involved a shorted heating element was reviewed. The report states that dryer's heating coil had broken and made contact with the dryer chassis. The timer was in the "on" position, but the tumbler was not rotating at the time. This incident involved the dryer overheating.

Based on the NFPA report and the review of CPSC IDI reports, the following abnormal operating conditions were chosen for this project.

1. Overfilled drum
2. Electric coil partial short-circuit
3. Fully or partially blocked lint screen
4. Fully or partially blocked exhaust duct
5. Air leaks
6. The presence of combustible vapors
7. Smoldering combustion
8. Flaming combustion
9. Spontaneous combustion.

Modifying the test clothes dryer or changing the condition of the dryer load simulated these abnormal operation modes.