TECHNICAL FEASIBILITY OF A CO SHUTDOWN SYSTEM FOR TANK-TOP HEATERS

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This report was prepared by the CPSC Staff, and has not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

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EXECUTIVE SUMMARY

One of the strategic goals of the U.S. Consumer Product Safety Commission (CPSC) is to reduce the carbon monoxide (CO) poisoning death rate by 20 percent by 2013. In support of this goal, CPSC staff began a project in fiscal year 2002 to study the technical feasibility of an automatic safety shutoff system that would prevent tank-top heaters from generating hazardous levels of CO, when operating the heaters in poorly ventilated confined spaces, such as tents or trailers. Although the intended use of tank-top heaters is in well-ventilated areas, some consumers have used the heaters in confined spaces that are poorly ventilated. In these situations, consumers may not provide proper ventilation, because it may seem counter-intuitive to open a door or window when they are trying to stay warm. Without proper ventilation, oxygen depletion occurs, impairing the combustion process and causing the heaters to generate CO more rapidly. This presents a CO poisoning hazard to consumers that could result in death or serious injury. Between January 1996 and June 2003, CPSC staff investigated 35 incidents involving tank-top heaters that resulted in the death of 49 individuals.

An automatic safety shutoff system requires two components: a sensor to detect that a hazardous condition may exist, and a mechanism to shut off the heater. Tank-top heaters are currently equipped with a flame failure shutoff system that prevents gas from flowing to the burner when a flame is not present. The shutoff system consists of a thermocouple, which senses the heat from the flame, and an electromagnetic gas valve powered by the thermocouple. Because this shutoff system already exists on tank-top heaters, it may be possible to combine it with a sensor that is capable of detecting when a hazardous CO condition exists, thereby creating a CO shutoff system.

CPSC staff operated a tank-top heater in an oxygen-depleted environment to observe how the O_2 concentration affected the CO emissions from the heater and how the overall performance of the burner was affected. The tank-top heater selected for the tests was one readily available to consumers at local hardware stores and was similar in design to heaters offered by other manufacturers. The oxygen depletion tests illustrated that the rate of CO generated by the heater is, in general, a function of the O_2 concentration in the room. There is a critical O_2 concentration (~16 percent), below which the CO increases very rapidly. In addition, as the O_2 concentration decreased, the flame tended to burn farther from the burner and the overall length of the flame increased. A change in the flame characteristics affected the temperatures on the heater and near the heater. The flame eventually self-extinguished when the oxygen concentration was insufficient to support the combustion process (~13 percent O_2).

Based on the results of the oxygen depletion tests, CPSC staff considered two types of CO shutoff systems. The first system would use a chemical sensor to detect the CO concentration near the heater. This system has the advantage of detecting the CO concentration directly, but has the disadvantage of requiring an external power source, such as batteries, to operate. The second system would use a thermal sensor to detect a change in the temperature on or near the heater, which is caused by a decrease in the O_2 concentration. The advantage of a thermal sensor is that some sensors are available that require no external power to operate. The disadvantage with a thermal sensor is that the CO concentration is not measured, but is inferred from the O_2 concentration, which in turn is inferred from a temperature measurement.

CPSC staff designed and tested one CO shutoff system. The system combined a residential CO alarm with the heater's existing flame failure shutoff system. In addition, the CO alarm was powered using a thermoelectric generator, which converted heat into electricity, thereby eliminating the need for batteries. The system successfully shut the heater off when a hazardous level of CO was detected within an enclosed room.

Based on some preliminary tests, CPSC staff believes that an automatic CO shutoff system for tank-top heaters is technically feasible. This report is intended as a first step in the development of a potential CO shutoff system for tank-top heaters. Additional testing and development work would be necessary to explore the practicality of various CO shutdown system designs.

1. INTRODUCTION

1.1 Background

According to the most recent data available, staff at the U.S. Consumer Product Safety Commission (CPSC) estimates that there were 13 deaths in the year 2000 due to non-fire carbon monoxide (CO) poisonings associated with unvented portable propane heaters (Vagts, 2003). Portable propane heaters can generate elevated levels of CO when operated in poorly ventilated confined spaces, such as in tents, campers, or trailers, in which minimum or no ventilation is provided. In calculating the death estimate, CPSC staff considered two types of unvented portable propane heaters: camp heaters and tank-top heaters. The primary difference between camp heaters and tank-top heaters is the size of the propane tank that fuels the heaters. Camp heaters primarily use a small disposable bottle of propane, which contains approximately 1-pound of liquid propane. Tank-top heaters use larger refillable tanks, such as a 20-pound tank commonly used on outdoor gas grills. The estimated number of yearly CO deaths attributable to either type of heater is unknown, because information provided to CPSC regarding a particular incident is not always complete. However, between January 1996 and June 2003, CPSC staff performed 52 in-depth investigations involving portable type propane heaters in which detailed information was available. Of the 52 incidents, 35 involved tank-top heaters, resulting in the death of 49 people. The remaining 17 incidents involved camp heaters and resulted in the death of 25 people.

Tank-top heaters are available in a variety of models, ranging from heaters equipped with a single radiant burner to heaters equipped with multiple radiant burners. Figure 1 (a) shows a tank-top heater equipped with a single radiant burner and Figure 1 (b) shows a tank-top heater equipped with dual radiant burners. In general, the maximum energy-input rate of a tank-top heater equipped with a single radiant burner is approximately 15,000 Btu/hr.[1] By combining several single radiant burners onto a common gas manifold, the overall energy-input rate of the heater can be increased. In a multiple burner configuration, the burners are independent of each other and can operate individually or together. Of the 35 incidents involving tank-top heaters investigated by CPSC staff between January 1996 and June 2003, only 18 of the incidents provided sufficient information to determine the energy-input rate of the heater. As shown in Table 1, 14 of the 35 incidents had a maximum energy-input rate between 12,000 Btu/hr and 15,000 Btu/hr, and four heaters had a maximum energy-input rate between 24,000 Btu/hr to 45,000 Btu/hr. The energy-input rate of the remaining 17 heaters is unknown.

(a) Single burner (b) Dual burner

Figure 1. Examples of a single burner tank-top heater and a dual burner tank-top heater

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[1] At least one manufacturer has designed a single radiant burner capable of rates up to 45,000 Btu/hr (Long, *et. al.*, 1997).

Table 1. The maximum energy-input rate of tank-top heaters involved in CO poisoning deaths, based on in-depth investigations by CPSC staff from January 1996 through June 2003 [1]

Maximum Energy-Input Rate of Heater	Number of Incidents	Number of Radiant Burners on Heater
12,000 to 15,000 Btu/hr	14	1
24,000 Btu/hr	1	2
30,000 Btu/hr	1	2
45,000 Btu/hr	2	1
Unknown	17	-

1. Information obtained by reviewing individual in-depth investigations listed in Vagts (2003).

Tank-top heaters consume oxygen as they operate. Therefore, the heaters are intended for use in well-ventilated areas, which can be defined as any space in which the oxygen in the surrounding atmosphere will not be depleted during the operation of the heater. One of the primary markets for tank-top heaters is the construction industry, which uses the heaters to provide temporary heat at construction sites. More recently, however, tank-top heaters have become readily available to consumers at do-it-yourself type hardware stores and camping supply stores. Consumers will often use tank-top heaters to provide temporary heat in "indoor" locations such as tents, trailers, fishing huts, cabins, or garages. In these situations, consumers may not provide proper ventilation, because it may seem counter-intuitive to open a door or window when they are trying to stay warm. Without proper ventilation, oxygen depletion occurs, impairing the combustion process and causing the heaters to generate CO more rapidly. As shown in Table 2, 20 of the 35 incidents investigated by CPSC staff occurred within tents and campers/trailers. A review of the individual incidents indicated that in 6 of the 35 incidents, the user attempted to provide ventilation, for example by cracking open a door or window, but did not appreciate or understand what constituted adequate ventilation, and was ultimately unsuccessful in providing sufficient ventilation.

Table 2. Locations of incidents, deaths, and non-fatal exposures associated with tank-top heaters, based on in-depth investigations by CPSC staff from January 1996 through June 2003 [1]

Location of Incident	Number of Incidents	Number of Deaths	Number of Non-Fatal Exposures
Tent	10	18	0
Camper/Trailer	10	12	1
Apartment/House/Garage	5	5	3
Other [2]	4	6	0
Auto [3]	3	4	0
Fish House	3	4	1
Total	**35**	**49**	**5**

1. Vagts, 2003
2. "Other" category includes a cube van, enclosed deer blind, wood frame building, and a cabin with attached trailer
3. "Auto" category includes passenger vans, passenger cars, and cabs of semi trucks

As part of CPSC's strategic goal to reduce the overall CO poisoning death rate by 20 percent by 2013, CPSC staff began a project in FY2002 to study the technical feasibility of an automatic safety shutdown device for tank-top heaters that would shut the heater off before hazardous levels of CO accumulated in a poorly ventilated confined space. This project was an add-on to the Camping Heater Project, which concluded in FY2002. The objective of the Camping Heater Project was to document the CO emissions from currently available propane-fired camping heaters and determine whether these heaters complied with the combustion requirements in the *American National Standard for Portable Type Gas Camp Heaters*, *ANSI Z21.63-2000*. Revisions were made to the voluntary standard in April 2000 that limited the amount of CO that a heater can produce when operated in a confined space with a limited air exchange rate. The standard also limits the amount that the heater can deplete the oxygen in the room during the test. Details of the Camp Heater Project are provided in a final project report (Tucholski, 2002). Although ANSI Z21.63 covers some tank-top heaters, not all tank-top heaters are covered by this voluntary standard, because the energy-input rate of some heaters exceeds the maximum limit specified in the scope of the standard. Section 1.3 of this report discusses the different voluntary standards that apply to tank top heaters.

1.2 Tank-Top Heaters

Tank-top heaters considered in this report are of the infrared radiant type[2], such as the heaters shown in Figure 1. Although the design of the actual burner may differ among manufacturers, the operation is similar.[3] Figure 2 is a drawing of a typical tank-top radiant heater. In general, the radiant burner assembly consists of at least two screens of varying mesh size: the burner head screen and the primary radiating screen.[4] The propane and air mixture burns just beyond the surface of the burner head screen. Heat generated by the combustion process heats the primary radiating screen, causing it to glow incandescent. The primary radiating screen is placed near the burner head to allow for maximum heating, but far enough away to prevent direct flame impingement, which would increase the amount of CO produced by the heater. The primary radiating screen radiates heat in all directions, heating nearby objects. A heat reflector surrounds the radiant burner assembly, directing the radiant heat out in front of the heater.

Tank-top heaters connect to any bulk tank of liquid propane equipped with a CGA 510 (POL type) connector. The heater may mount directly or indirectly to the propane tank, depending on the type of heater. The heater shown in Figure 1 (a) is an example of a direct-mount heater. In this configuration, the gas piping (e.g., mixing tube) supports the heater assembly to the propane tank. The heater shown in Figure 1 (b) is an example of an indirect-mount heater. In this configuration, a separate support assembly independent of the gas piping attaches the heater assembly to the tank, and a gas hose conveys the propane from the tank to the heater assembly. Both types of heaters generally have the pressure regulator built into the manual control valve assembly. The manual control valve controls the amount of fuel supplied to the burner. Typically, the heater has three distinct settings: High, Medium, and Low. The heater may also have a built-in ignition source, such as a piezo-type electronic igniter, to ignite the gas mixture when starting the heater. If the heater does not have a built-in ignition source, the user must provide one, such as a lighter.

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[2] Of the 35 in-depth investigates conducted by CPSC staff between 1996 and June 2003 involving tank-top heaters, two of the heaters were described as catalytic. A catalytic heater generates heat from a flameless catalytic reaction involving propane and oxygen, while a flame is present in the operation of an infrared radiant heater. When photographs from one of the reported catalytic heater incidents were examined, the heater appeared to be infrared.

[3] This discussion of radiant burners is not meant to provide a detailed explanation about radiant burner designs or the theory behind radiant burners, but rather to provide a general overview to those not familiar with these types of burners.

[4] In some designs, a porous ceramic plaque is used as the burner, which also acts as the primary radiating surface.

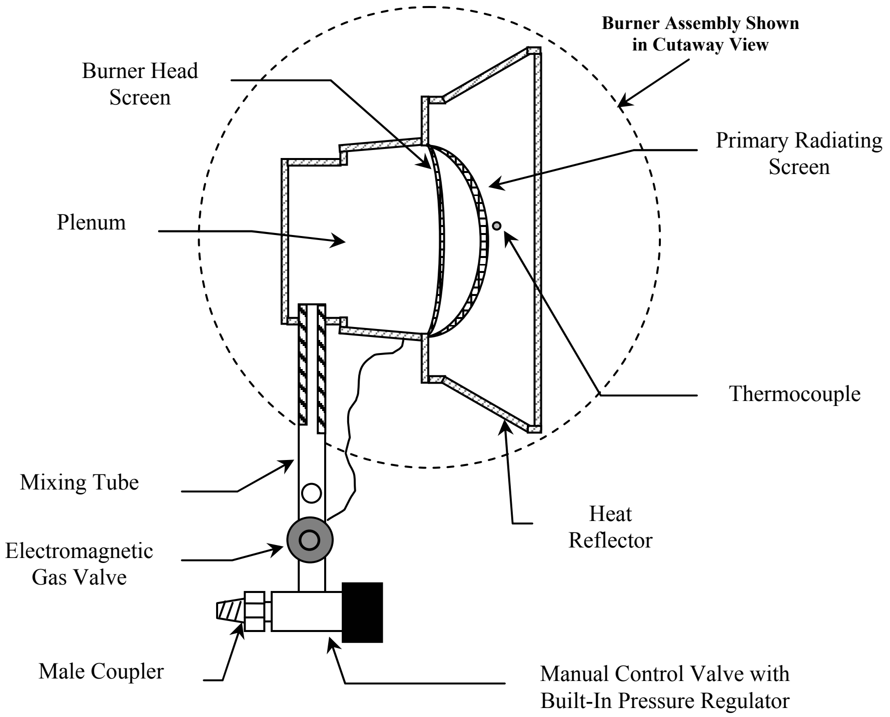

Figure 2. Drawing of a typical tank-top radiant heater

Tank-top heaters are currently equipped with a flame failure shutoff device that prevents gas from flowing to the burner if the flame goes out. As shown in Figure 3, the flame failure shutoff device consists of an electromagnetic gas valve connected to a thermocouple, which is located in front of the radiant burner. Heat from the burner heats the thermocouple, and the thermocouple then converts the heat into electricity. The electrical current flows from the thermocouple to the gas valve, where it energizes an electromagnet. Because the magnetic force generated by the electromagnet is small compared to the force required to compress the spring-loaded valve in the gas valve, the valve must be manually opened during the startup of the heater by pressing and holding the manual override button. The magnetic force generated by the electromagnet is then sufficient to hold the gas valve open, allowing gas to flow to the burner. When the flame is extinguished, the thermocouple will cool, and the spring-loaded gas valve will close automatically.

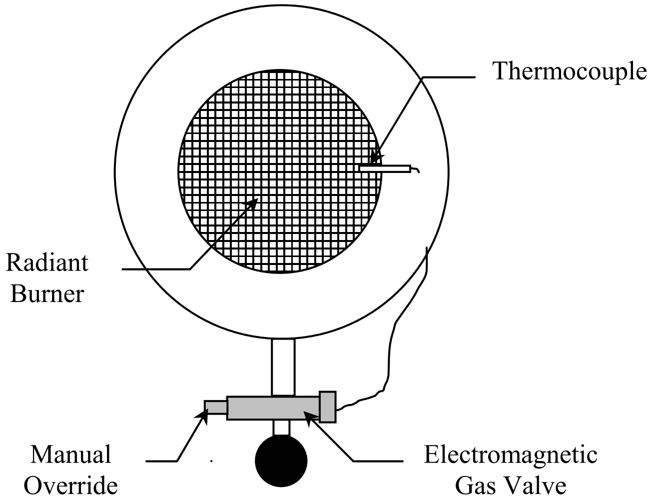

Figure 3. Flame failure shutoff device on tank-top heaters

1.3 Voluntary Standards

Different voluntary standards cover tank-top heaters, depending on the energy-input rate of the heater, and the construction of the heater. Heaters whose maximum energy-input rate setting is 12,000 Btu/hr or less are within the scope of the voluntary standard for portable type gas camp heaters (ANSI Z21.63). In general, ANSI Z21.63 applies to unvented portable type gas-fired heaters, of the infrared type, that are intended for outdoor use, and have a maximum input rate up to and including 12,000 Btu/hr. The combustion requirement in the voluntary standard specifies that when the heater is operated in a 100 cubic foot room having an air exchange rate of 0.5, 1.0, and 1.5 air changes per hour (ACH), the CO concentration in the room cannot exceed 100 parts per million (ppm). In addition, the oxygen (O_2) concentration in the room cannot be depleted below 16 percent during the test.

Tank-top heaters rated at more than 12,000 Btu/hr and that mount *directly* to a propane tank are currently not covered by any voluntary standard. Prior to the year 2000, the construction heater standard (ANSI Z83.7) provided coverage for direct-mount radiant heaters. However, the coverage was apparently dropped when the United States and Canada harmonized their respective standards for construction heaters in the year 2000. Because these heaters are currently not covered by any standard, CPSC staff has voiced its concerns to members of the Technical Advisory Groups for the voluntary standards for Construction Heaters (ANSI Z83.7), Camp Heaters (ANSI Z21.63), and Infrared Heaters (ANSI Z83.19/Z83.20). To date, no action has been taken by any of these groups to provide coverage for direct-mount tank-top heaters rated at more than 12,000 Btu/hr.

Tank-top heaters rated at more than 12,000 Btu/hr and that mount *indirectly* to a propane tank (e.g., Figure 1 (b)) are within the scope of the voluntary standard for construction heaters (ANSI Z83.7), provided that the heaters are equipped with a hose assembly (i.e., gas hose and end fitting) and are equipped with an ANSI/UL 144 approved pressure regulator. According to ANSI Z83.7, the hose assembly can be eliminated if the gas piping of the heater does not support the burner assembly. The combustion requirement in ANSI Z83.7 specifies that when the heater is operated in a room having a normal oxygen supply (~20.9 percent), the CO emitted by the heater cannot exceed 0.08 percent (800 ppm) on an air-free basis. The voluntary standard does not require the heaters to be tested in a room having a reduced oxygen supply, as is required by the voluntary standard for camp heaters.

2. AUTOMATIC CO SHUTOFF SYSTEMS

2.1 Overview

An automatic safety shutoff system for gas-fired heaters requires two components: a sensor to detect that a hazardous condition may exist, and a mechanism to shut the heater off when activated by the sensor. Tank-top heaters are equipped with a flame failure shutoff device that prevents gas from flowing to the burner when the flame goes out. The flame failure shutoff device consists of a thermocouple, which senses the heat from the flame, and an electromagnetic gas valve, which is powered by the thermocouple. Because this shutoff system already exists on tank-top heaters, it may be possible to combine the heater's flame failure shutoff device with a sensor that can detect when a hazardous CO condition may exist, thereby creating a CO shutoff system.

2.2 Sensing Technologies

The sensing technologies considered in this report fall into two general categories: those that sense a change in the CO concentration and those that sense a change in the O_2 concentration. Although technologies other than those discussed in this report exist, they are generally not suited for a portable heater application due to several factors, including electrical power requirements, the size of the equipment, or the fragility of the equipment.

2.2.1 Carbon Monoxide

Carbon monoxide can be detected directly using a chemical sensor. There are various sensor technologies available, each with different advantages and disadvantages. Electrochemical sensors and semiconductor sensors are commonly used in residential CO alarm applications. Although not as common, a residential CO alarm with a biotechnology-based gas sensor is also available.

Electrochemical sensors consists of a gas-permeable membrane, two electrodes (anode and cathode), and an electrolyte that separates the electrodes. When CO diffuses through the membrane, it is oxidized to CO_2 on the anode. Ions generated by the reaction flow to the cathode, where a reduction reaction takes place. The flow of ions between the electrodes produces an electrical current that is proportional to the CO concentration. Some advantages of an electrochemical sensor are that the output signal of the sensor is linear and the sensor can detect CO concentrations at the parts-per-million (ppm) level. Some disadvantages of an electrochemical sensor are the narrow temperature range in which the sensor can operate, the relatively short shelf life of the sensor, and that the sensor life will be shortened in very dry and very hot areas.

Semiconductor sensors operate on the principle that the conductivity of certain materials can change in the presence of a specific gas. In the presence of CO, oxygen absorbed at the surface of the sensor reacts with CO, causing an increase or decrease in the surface electrons, depending on the semiconductor material. A change in the number of surface electrons results in a change in the conductivity of the sensor. The change in resistance of the sensor is directly proportional to the change in the CO concentration. In the past, the sensors were a metal oxide semiconductor (MOS), such as tin dioxide. These sensors were susceptible to humidity and temperature effects. Newer sensors are available that are mixed metal oxide semiconductors (MMOS), such as chromium titanium oxide. The MMOS sensors are projected to have a longer life and are less susceptible to the effects of humidity than the MOS sensors. Other advantages of semiconductor sensors are as follows: small size, mechanically rugged, can detect CO concentrations in the ppm range, and can operate in a wide temperature range. A disadvantage of semiconductor sensors is that the output signal of the sensor is non-linear.

Biotechnology-based gas sensors use a genetically engineered organic material to detect CO. The sensor consists of a porous, semi-transparent substrate that is impregnated with a self-regenerating chemical sensor reagent. Light is transmitted through the sensor using a light emitting diode (LED) and is detected using a photodiode. When exposed to CO, the sensor darkens and less light is transmitted through the sensor. The amount of light transmitted is proportional to the CO concentration. Because this sensor is unique to one manufacturer, little information is known about the sensor. The manufacturer of the sensor claims that the sensor is able to mimic the human body's response to carbon monoxide exposure and is therefore, good at determining long-term, low-level exposures to CO, as well as high-level CO exposures. CPSC staff has not tested this particular sensor.

2.2.2 Oxygen

The rate of CO generated by a gas-fired portable heater is generally a function of the O_2 concentration and therefore, is sometimes used as a proxy for CO concentration.[5] The exact relationship between the O_2 concentration and the CO concentration will be different for different heaters. However, tank-top heaters generally start to produce CO more rapidly after the O_2 concentration has been depleted below a critical concentration, which may be different for similar heaters. Even for "identical" heaters (i.e., same model), the critical O_2 concentration may be slightly different, due to normal variations that may occur during the manufacturing process of the heater. By shutting the heater off before the oxygen is depleted below the critical O_2 concentration, the heater should not produce hazardous levels of CO. The O_2 concentration can be detected directly using a chemical sensor or indirectly using a thermal sensor.[6]

2.2.2.1 *Chemical Sensor*

Oxygen can be measured directly using a chemical sensor. Although there are different types of sensors available for the measurement of O_2, an electrochemical sensor is commonly used for the measurement of oxygen in residential appliance applications. The electrochemical sensor for O_2 measurement is similar to the electrochemical sensor for CO measurement in that it consists of a gas-permeable membrane, two electrodes, and an electrolyte, which separates the electrodes. When O_2 diffuses through the membrane, it is reduced to hydroxyl ions (OH^-) on the cathode. The ions flow through the electrolyte to the anode, where a counter oxidation reaction takes place. The flow of ions between the electrodes produces an electrical current that is proportional to the O_2 concentration. Because the electrochemical sensor generates its own power, no electrical power is required to operate the sensor. However, power will be required to operate any additional circuitry used to process the output signal from the sensor.

2.2.2.2 *Thermal Sensor*

For gas-fired equipment, it is often possible to infer the O_2 concentration from a temperature measurement of the flame. This technique is possible because the O_2 concentration affects several aspects of a flame. In particular, the O_2 concentration affects the burning velocity of the flame and the length of the flame. As the O_2 concentration decreases, the burning velocity of the flame decreases. A decrease in the burning velocity results in the flame burning farther away from the burner, because the burning velocity acts in a direction directly opposite to the flow of the unburned gas/air mixture. This phenomenon is known as flame lift. As the O_2 concentration decreases, the flame will burn farther away from the burner, until a certain O_2 concentration is reached and the flame will self-extinguish. In addition to flame lift, the length of the flame increases as the O_2 concentration decreases, because there is less oxygen available to burn all of the fuel. With less oxygen available, more time is required to burn the fuel

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[5] In general, the rate at which a heater generates CO is a function of the O_2 concentration. However, there are exceptions. For example, a heater may generate excess CO when operating in a room with a normal oxygen concentration ($O_2 \sim 20.9$ percent), if there is a problem with the burner (e.g., some of the burner ports are blocked, the air inlet for the combustion air is partially/fully blocked, etc.). An O_2 sensor will not prevent the heater from generating excess CO in this situation.

[6] Although not discussed in this report, a carbon dioxide (CO_2) sensor could be used instead of an O_2 sensor, because of a linear relationship that exists between the consumption of oxygen and the formation of carbon dioxide during the combustion of a hydrocarbon fuel.

and hence, a longer flame results. As the flame length increases, it may contact certain parts of the heater not normally contacted by the flame. By placing a thermal sensor either directly into the flame or near the flame, the flame temperature can be detected. Depending on the location of the thermal sensor, the temperature may either increase or decrease as the O_2 concentration decreases. Combining the relationship between temperature and the O_2 concentration, and the relationship between the CO concentration and the O_2 concentration, one can derive a relationship between temperature and CO.

Various types of thermal sensors are available to detect the temperature. Some thermal sensors require an external power source to operate, while other types do not. Thermocouples and bimetallic switches are examples of thermal sensors that do not require an external power source to operate.

2.2.2.2.1 Thermocouple

A thermocouple is a device that converts heat into electricity. In its simplest form, the thermocouple consists of two dissimilar metal wires joined together at one end to form a junction, known as the hot junction. When the hot junction is heated, a voltage potential exists between the two free wire ends. The voltage potential is a function of the junction temperature and the wire materials.

Thermocouples are commonly used to measure temperature and are sometimes used as part of a gas safety system. The design of the thermocouple is different, based on the application. Thermocouples designed for temperature measurement consist of two dissimilar metal wires joined together at one end to form the hot junction. A cold junction is formed when the free ends of the wires are connected to a meter, which is used to measure the generated voltage. The cold junction is typically located some distance away from the hot junction, such that the cold junction is not affected by the heating of the hot junction.

Thermocouples designed for gas safety systems are a rod-and-tube type configuration, as shown in Figure 4. The head of the thermocouple forms the hot junction and consists of an inner rod of Constantan (CuNi) soldered to an outer cap of either Nickel-Chrome (NiCr90/10), Inconel 600 (NiCrFe), or Ferro-Chrome (FeCr). Unlike thermocouples used for temperature measurements, thermocouples used for gas safety systems have the cold junction located relatively close to the hot junction (~ 0.8 to 1.2 inches). One cold junction is formed on the exterior of the thermocouple where the outer cap of the thermocouple head is soldered to the "pipe", which is made of brass. The other cold junction is formed on the inside of the thermocouple where the inner rod of the thermocouple made of CuNi is connected to a rod made of a copper. The exterior of the thermocouple (i.e., tube) forms the electropositive element of the thermocouple, and the interior (i.e., rod) forms the electronegative element.

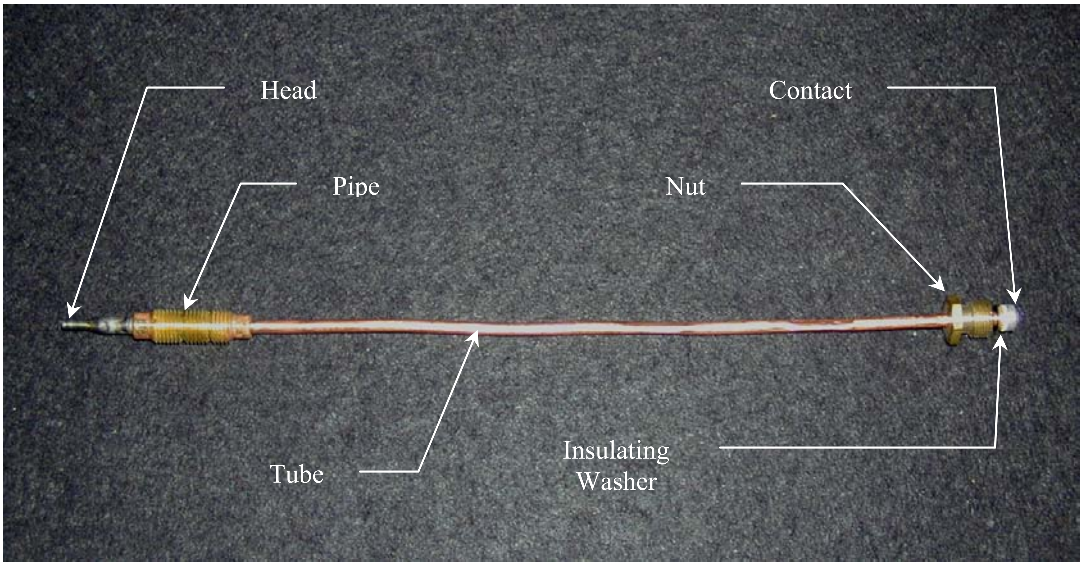


Figure 4. Example of a rod-and-tube type thermocouple currently in use on tank-top heaters

In general, the voltage generated by a thermocouple is a function of the material of the thermocouple and the temperature difference between the hot junction and the cold junction. When the hot junction of the thermocouple is heated, the temperature at the hot junction will increase exponentially with time. For rod-and-tube type thermocouples, the cold junction is located relatively close to the hot junction. Therefore, the temperature at the cold junction will also increase exponentially, due to the thermal conduction of heat through the metal. The cold junction will increase at a rate slower than the rate at which the hot junction increases, because of the different materials. The net result is that the voltage generated by a rod-and-tube type thermocouple will increase exponentially, reach some maximum, and then decrease to a steady state value. The steady state voltage is less than the peak voltage, because the temperature at the cold junction increases over time, resulting in a smaller temperature differential between the hot junction and the cold junction.

The location of the heat source will greatly affect the voltage generated by a rod-and-tube type thermocouple because of the relatively close proximity of the cold junction relative to the hot junction. The maximum voltage generated by the thermocouple will be obtained when the heat source contacts only the tip of the thermocouple. As the heat source is moved towards the cold junction, the generated voltage will decrease significantly.

2.2.2.2.2 Bimetallic Switch

A bimetallic thermal switch is a device that makes or breaks an electrical contact when the design temperature has been exceeded. Bimetallic switches operate on the principle that when two different materials are heated, they will expand at different rates, due to the different thermal expansion coefficients of each material. There are various configurations for bimetallic switches, such as a disc, a strip, and a rod-and-tube. The switch can be designed to either open or close when the design temperature is reached. The design temperature can range from a few hundred degrees to over 1000°F, depending on the configuration of the bimetallic switch.

2.3 Shutoff Systems

CPSC staff considered several types of shutoff systems to prevent tank-top heaters from producing hazardous levels of CO when the heaters are operated in confined spaces that are poorly ventilated. Staff searched the *United States Patent and Trademark Office* database to determine if any patents have been awarded for a CO shutoff system specifically designed for tank-top heaters. Staff also considered shutoff systems that are currently in use on other types of gas-fired equipment. Finally, staff considered other shutoff systems based on observations made of a tank-top heater operating in an oxygen-depleted environment. The following shutoff systems considered by staff are not meant to be comprehensive, but were the ones that were considered by staff in the time allotted for the project.

2.3.1 CO Alarm

In order to incorporate a CO sensor into a shutoff system, the relationship between the output signal from the sensor (e.g., voltage or current) and the CO concentration must be known. Additional circuitry is generally required to condition the output signal of the sensor before it can be used. Use of a residential CO alarm in a shutoff system has the advantage that the CO alarm already contains all the required circuitry to measure the CO concentration and alarm at hazardous conditions.

A CO shutoff system can be designed that uses a residential CO alarm in combination with the heater's existing flame failure shutoff device, which consists of a thermocouple and an electromagnetic gas valve. An electrical switch that is activated by the CO alarm can be connected between the thermocouple and the electromagnetic gas valve. When the CO detector alarms, the current flowing between the thermocouple and the gas valve would be interrupted, causing the gas valve to close.

One company has designed a portable shutoff system for gas appliances. The shutoff system, which is shown in Figure 5, consists of a CO alarm powered by a 9-volt battery, a field-effect transistor (FET), and a connector that connects the thermocouple and solenoid gas valve with the FET. The FET acts as an electrical switch between the thermocouple and the electromagnetic gas valve. Under normal conditions, the CO alarm supplies the required voltage to power the FET, which allows the current from the thermocouple to flow to the gas valve. When hazardous levels of CO are detected, the alarm sounds and the voltage supplied from the CO alarm to the FET drops to zero. Without power, the FET acts as an open switch, thereby blocking the flow of current to the gas valve, causing the gas valve to close. Similar shutoff circuits can be designed using different types of CO alarms and/or electrical switches.

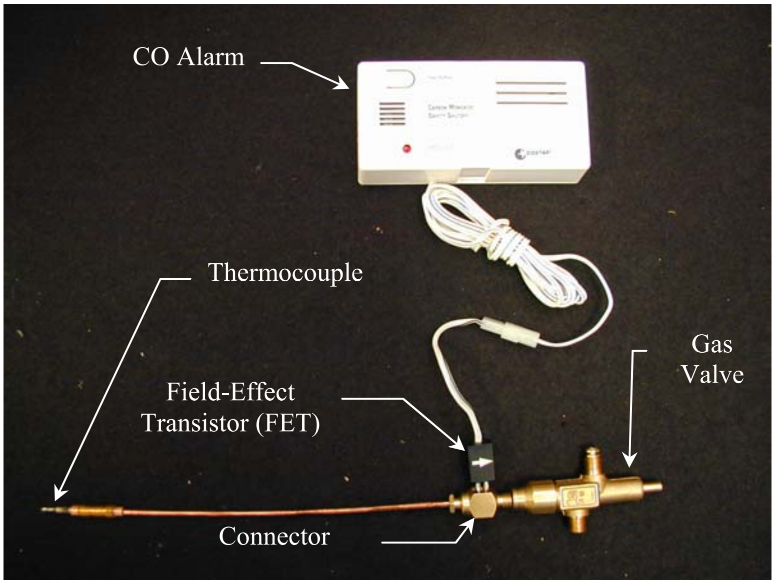


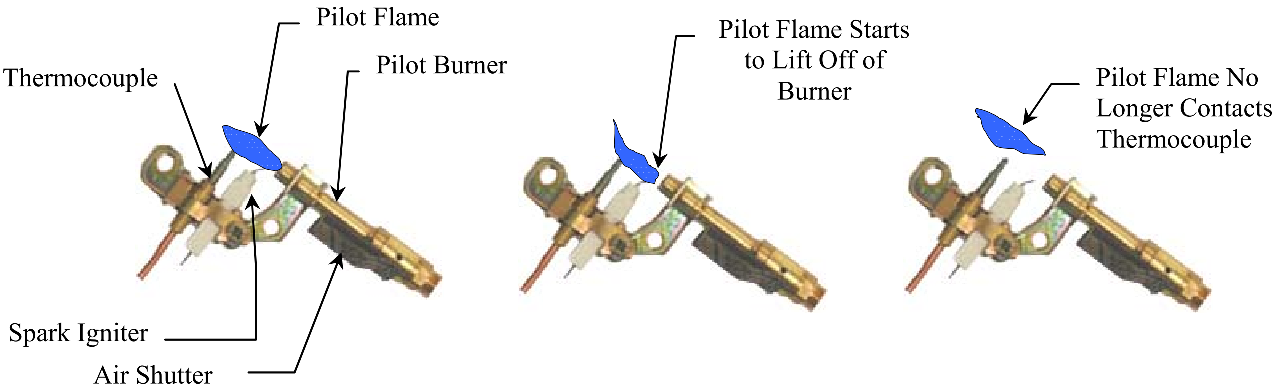
Figure 5. CO shutoff system for gas appliances

2.3.2 Thermal Sensor

2.3.2.1 *Oxygen Depletion Sensing System*

One type of CO shutoff system that has been used successfully on unvented gas-fired room heaters sold in the United States since the 1980's is an Oxygen Depletion Sensing System, more often referred to as an Oxygen Depletion Sensor (ODS). Recently, several manufacturers of camping heaters have included an ODS on some of their heaters, thereby allowing the heaters to be used indoors safely.

As shown in Figure 6, the ODS consists of a pilot burner and a thermocouple, which is connected to an electromagnetic gas valve (not shown). The flame on the pilot burner is very sensitive to slight changes in the O_2 concentration. When the O_2 concentration in the room is normal (~ 20.9 percent), a blue flame exists on the pilot burner and the flame contacts the tip of the thermocouple. As the flame contacts the thermocouple, a small voltage and current are generated, which are sufficient to energize the electromagnet in the gas valve. Once energized, the electromagnet can hold open the gas valve, allowing gas to flow to the main burner. With a slight decrease in the O_2 concentration, the flame begins to lift off the burner, but the flame still contacts the thermocouple, so the gas valve remains open. When the O_2 concentration is depleted below 18 percent, the flame lifts completely off the burner, past the tip of the thermocouple. The thermocouple then cools, causing the gas valve to close.



Normal Oxygen
$O_2 \sim 20.9$ %

Reduced Oxygen
$18\% < O_2 < 20.9\%$

Shutoff
$O_2 < 18$ %

Figure 6. Illustration of an Oxygen Depletion Sensor (ODS)

2.3.2.2 *Thermocouple Located Behind Burner Head Screen*

Staff searched the *United States Patent and Trademark Office* database and located only one patent that described a CO shutoff system specifically designed for tank-top heaters. Patent 5,941,699 (Abele, 1999) was awarded in August 1999 to a current manufacturer of portable propane heaters. The shutoff system, which is shown in Figure 7, consists of a thermocouple connected to a modified electromagnetic gas valve. The thermocouple is placed in the plenum area behind the burner head screen and is able to detect small changes in the screen temperatures. When oxygen depletion occurs, the flame will degrade over certain portions of the screen, which is sensed by the thermocouple as a decrease in temperature. Following this decrease in temperature, there is an increase in the temperature, which coincides with an increase in the CO concentration. Therefore, a correlation between temperature and CO can be obtained, which is unique to a particular burner design. When the temperature sensed by the thermocouple decreases, the current generated by the thermocouple decreases, resulting in a decrease in the magnetic field generated by the coil in the gas valve. A proximity sensor, such as a Hall-effect sensor, which is attached to the gas valve, is used to detect the decrease in the magnetic field generated by the coil. Once a decrease in the magnetic field is detected, the proximity sensor acts as a switch and interrupts the flow of current between the thermocouple and the electromagnetic gas valve. The gas valve then closes, shutting off the gas to the burner.

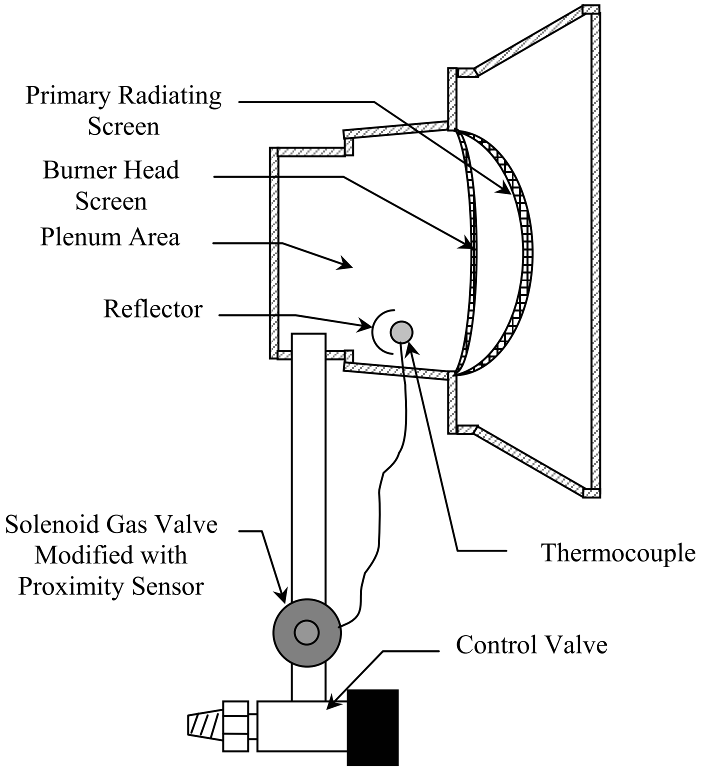


Figure 7. Drawing of CO shutoff system for a tank-top heater (US Patent 5,941,699)

2.3.2.3 *Thermocouple Located In Other Areas*

The shutoff system described in Patent 5,941,699 uses a thermocouple located in the plenum area behind the burner head screen to detect small changes in the screen temperatures. Staff thought that it might be possible to locate a thermocouple in a different location that may offer a similar or better response. For this shutoff system, the thermocouple would be connected to an electromagnetic gas valve and the valve would close when the temperature dropped below the voltage required to energize the electromagnet.

2.3.2.4 *Bimetallic Switch*

When a tank-top heater was operated in an oxygen-depleted environment, flame lifting was observed and the length of the flame was observed to increase. Therefore, staff thought that it might be possible to use a bimetallic switch, which would activate as the temperature either increased or decreased beyond the set point temperature of the switch. The bimetallic switch would be placed in series with the thermocouple and the electromagnetic gas valve. When the bimetallic switch activates, the switch would open and interrupt the flow of current between the thermocouple and the gas valve. The gas valve would then close, shutting off the gas to the burner.

2.4 Electrical Power Supply

Ideally, the CO shutoff system should not require an external power source, such as batteries, to operate. Batteries have a limited life, and consumers may not always have a replacement battery when needed. Depending on the power requirements, it may be possible to generate the power using a thermoelectric device, which is a device that uses heat to generate electricity. For very low power applications (approximately 20 to 30 mV), a thermocouple can be used. For slightly higher power applications (less than 1 volt), a group of thermocouples connected electrically in series (i.e., thermopile) can be used. For higher power applications, a thermoelectric generator can be used. A thermoelectric generator is similar to a thermopile in that it consists of a group of thermocouples connected electrically in series. However, unlike a thermopile, which uses thermocouples fabricated from metal wires, a thermoelectric generator uses thermocouples fabricated from semiconductors. The semiconductors are placed within a module so that all of the thermocouples are parallel to the heat flow and are connected electrically in series.

Depending on the operating temperature of the thermoelectric module, different semiconductor materials are used. For applications up to several hundred degrees, Bismuth Telluride (Bi_2Te_3) based semiconductors are commonly used. The power output of a thermoelectric module is proportional to the total-module cross sectional area, and inversely proportional to the module thickness. In addition, the power output is proportional to the number of thermocouples in the module. In order to generate power, a large temperature drop is required across the relatively thin module. For example, one thermoelectric module that is capable of generating 2.5 watts of power requires a temperature difference of 365°F across a distance of 0.2 inches.

3. EXPERIMENTAL TESTS[7]

3.1 Heater Samples

Tests were conducted using three identical (i.e., same model) heaters from one manufacturer. This particular heater was selected because it is readily available to consumers, and the design of the heater is similar to other heaters on the market. In this report, the three test samples are referred to as Heater A, Heater B, and Heater C. Figure 8 is a photograph of one of the test samples. The maximum energy-input rate, as specified by the manufacturer was 14,000 Btu/hr. The minimum energy-input rate, as specified by the manufacturer, was 8,000 Btu/hr. The heaters were attached directly to 20-pound tanks of liquid propane, which were purchased from a local hardware store.

Figure 8. Photograph of sample tank-top heater used in tests

3.2 Oxygen Depletion Tests

Each tank-top heater was operated in an oxygen-depleted environment to observe how the O_2 concentration affected the rate of CO generated by the heater and to observe how the O_2 concentration affected the heater's flame.

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[7] The test equipment described herein including specific manufacturers' products used to monitor or control testing, and/or record or obtain data, is specifically identified to allow others to attempt to re-produce this work should they so desire. Mention of a specific product or manufacturer in this report does not constitute approval or endorsement by the Commission.

3.2.1 Experimental Setup

The oxygen depletion tests were conducted inside a 100 ft^3 test chamber that had an interior height of 6.6 ft, a width of 3.9 ft, and a depth of 3.9 ft. The chamber was constructed from sheets of fire retardant boards supported by a metal framework. A chilled water heat exchanger system was used to maintain the temperature inside the chamber at a set temperature. The cooling system could maintain the chamber temperature at 80°F ± 5°F for heaters rated up to 15,000 Btu/hr. To enhance the heat transfer of the cooling system, fans were used to move air over the cooling coils of the heat exchanger. These fans also circulated the air within the chamber, which resulted in a well-mixed environment. The air exchange rate through the chamber could be varied from 0 to 6 air changes per hour (ACH) by controlling the speed of the supply fan and exhaust fan, and by changing the diameter of the opening for the supply air.

Gas samples were continually withdrawn from the chamber through six equal length sample lines located within the chamber. The six sample lines were connected to a common manifold where the gas samples mixed. A pump conveyed the mixed gas sample to a series of gas analyzers. The gas sample was analyzed for CO, CO_2, O_2, and unburnt hydrocarbons measured as propane gas (C_3H_8). Table 3 provides a summary of the gas analyzers. Water vapor formed during the combustion process was removed from the gas sample prior to analysis using a chilled water heat exchange system.

Table 3. Summary of gas analyzers

Gas Specie	Gas Analyzer			Measurement Range
	Measuring Technique	Manufacturer	Model	
CO	Non-Dispersive Infrared	Rosemount	880A	0 – 200 ppm 0 – 1,000 ppm 0 – 3,000 ppm
CO_2	Non-Dispersive Infrared	Rosemount	880A	0 – 10 percent
O_2	Paramagnetic	Rosemount	755R	0 – 20.9 percent
HC (C3H8)	Non-Dispersive Infrared	Rosemount	880A	0- 100 percent LEL[1]

1. LEL = Lower Explosive Limit; for propane gas, the LEL is 2.1 % propane in air.

The air temperature in the chamber was measured at six locations in the chamber using K-type thermocouples (28-gauge, Omega). One thermocouple was located at the inlet of each sample tube.

The air exchange rate in the chamber was determined experimentally by measuring the exponential decay of a tracer gas once the heater shut off. Sulfur hexafluoride (SF_6) was used as the tracer gas for all tests. The concentration of SF_6 in the chamber was measured with an electron capture gas chromatograph analyzer (Largus Applied Technology, Model 101 Autotrac). The air exchange rates obtained from the decay of SF_6 were verified by the decay of CO, which occurred once the heater was off.

The energy-input rate of the heater was determined indirectly by measuring the amount of propane-fuel consumed by the heater over time. The mass of fuel consumed during a given time interval was measured using an electronic scale (Mettler, PM34 Delta Range).

A data acquisition system was used to collect and record the data. The system consisted of a personal computer, data acquisition interface hardware (Keithely), and data acquisition software (Labtech Control). Gas concentrations and temperatures were recorded every 30 seconds by the data acquisition program. The program converted the voltage output from the gas analyzers into the appropriate concentration units (percent or parts per million). The only items not recorded by the data acquisition system were the concentration of SF_6 and the mass displayed on the electronic scale. The SF_6 analyzer contained an internal data acquisition program and recorded the concentration measurements directly to a 3.5-inch floppy disk located on the analyzer. The mass of fuel consumed was displayed on the electronic scale and recorded manually.

3.2.2 Experimental Procedures

The gas analyzers were calibrated each morning prior to any tests being conducted. Each gas analyzer was calibrated according to the instructions specified by the manufacturer. In general, the CO, CO_2, O_2, and HC gas analyzers were zeroed with nitrogen gas. The CO, CO_2, and HC analyzers were then spanned using gases of known concentrations (EPA Protocol Standards). Since the CO analyzer had three different ranges available, the gas analyzer was spanned on each range using a gas appropriate for that range. The O_2 analyzer was spanned using room air, assuming an O_2 concentration of 20.9 percent. The SF_6 analyzer was calibrated using a calibration gas supplied by the manufacturer of the SF_6 analyzer.

To begin a test, the air exchange rate of the test chamber was set by adjusting the speed of the inlet fan and the exhaust fan. The relationship between the fan speed (i.e., supply voltage) and the air exchange rate through the chamber was known prior to the tests. The chamber's cooling system was also started at this time. Because staff was interested in the effects of oxygen depletion on the performance of the tank-top heater, the air exchange rate was selected so that for a given energy-input rate setting of the heater, the oxygen was depleted to a point just prior to the flame self-extinguishing.

After completing the initial setup of the chamber, the heater, which was attached to a propane tank, was placed on the electronic scale inside of the chamber. The propane gas was then ignited following the instructions specified by the manufacturer of the heater. The gas control valve on the heater was adjusted to provide the desired energy-input rate of the heater. The door to the chamber was closed and the data acquisition program was then started.

As the test proceeded, the mass displayed on the electronic scale was recorded on a data sheet at various time intervals. As a back up to the data recorded electronically by the data acquisition system, the concentrations of CO, CO_2, O_2, and HC were periodically recorded manually on a data sheet.

The test proceeded until the concentrations of CO, CO_2, and O_2 reached equilibrium (steady state), or the flame self-extinguished. If the gas concentrations reached steady state, the heater was manually shut off by reaching into the chamber through a pair of glove ports and rotating the fuel control knob on the heater to the "Off" position. For tests in which the flame self-extinguished, the heater shut off automatically due to the flame failure safety device on the heater. Once the heater was off, the SF_6 analyzer was started and a small volume of SF_6 tracer gas was injected into the chamber. The decay of the SF_6 gas was then monitored, with the concentration of the gas being recorded every two minutes.

3.3 Heater Temperature Tests

Tests were conducted to determine if there was an optimal location to mount a thermal sensor, which could detect when the flame started to lift off the burner or when the flame started to elongate.

3.3.1 Experimental Setup

Heater A was used for the temperature tests. As illustrated in Figure 9, the surface temperature was measured at five locations (2, 3, 4, 5, and 7). Locations 2, 3, 4, and 7 were on the plenum of the burner assembly, and location 5 was on the backside of the heat reflector. In addition to the surface temperatures, the air temperature near the burner was measured at two locations (1 and 6). Location 1 was adjacent to the heater's existing thermocouple and was used to estimate the temperature sensed by the heater's thermocouple. Location 6 was above the burner, in front of the heat reflector.

The surface temperatures were obtained by welding K-type thermocouples (Omega, 24 gage wire) directly to the surface of the heater using a portable, capacitive, discharge welder (DCC Corporation, HotSpot, #10-A10120). For the air temperature measurements, K-type thermocouples (Omega, 24-gage wire) were held in place by securing the wires to a rigid piece of metal. The tip of thermocouple #1 was located 0.125 inches from the tip of the heater's thermocouple and 0.625 inches above the surface of the burner. Thermocouple #6 was positioned 0.875 inches off the surface of the heat reflector and 0.75 inches from the top of the heat reflector.

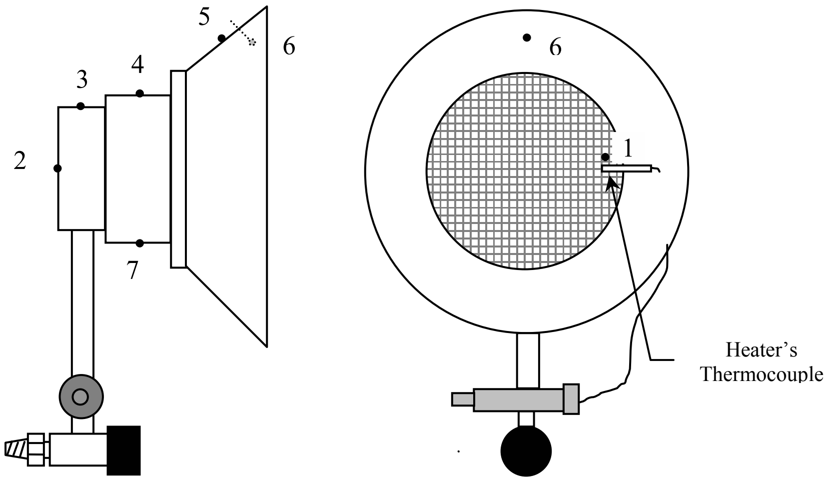


Figure 9. Location of thermocouples that measured the surface temperatures on the heater and the air temperature near the heater

The temperature data were recorded using a computer controlled data acquisition system. The data acquisition system consisted of a data acquisition module (Data Translation Inc., USB Module model 9805), a personnel computer, and a data acquisition program (Labtech Control). The data acquisition module could measure seven thermocouples simultaneously.

3.3.2 Experimental Procedures

To establish the baseline temperatures at each location under normal oxygen conditions, the heater was operated in a large room having a normal O_2 concentration (~20.9 percent). The heater was operated until all of the temperatures reached steady state. The temperature data was recorded at 5 second intervals using the data acquisition program. Tests were conducted with the heater operating at its maximum energy-input rate and its minimum energy-input rate.

The heater was then operated in an oxygen-depleted environment using the 100 ft^3 test chamber. The air exchange rate was adjusted so that the oxygen was reduced to a point just prior to the flame self-extinguishing. The heater was operated until all of the temperatures reached steady state. The temperature data was recorded at 5 second intervals using the data acquisition program. Tests were conducted with the heater operating at its maximum energy-input rate and its minimum energy-input rate.

3.4 Thermocouple Tests

Several of the shutoff systems considered by staff used a thermocouple as part of a CO shutoff system. In some of these systems, it is necessary to know how the voltage generated by the heater's rod-and-tube type thermocouple varied with temperature and the temperature at which the electromagnetic gas valve would engage and disengage. Staff contacted the manufacturer of the rod-and-tube type thermocouple on the test sample heater. The manufacturer did not provide specific information about this exact thermocouple, but rather provided general information about the rod-and-tube type thermocouples used as part of a gas safety system. Therefore, staff attempted to determine how the voltage generated by the rod-and-tube type thermocouple varied with temperature and the temperature at which the electromagnetic gas valve would engage and disengage.

3.4.1 Experimental Setup

Tests were conducted using a rod-and-tube type thermocouple identical to the one on the sample heater. The thermocouple was purchased directly from the manufacturer of the sample heater. The tip of the thermocouple was heated using a dry-well temperature calibrator (Hart Scientific, Model 9141 EZT). Temperatures up to 1200ºF were possible with the temperature calibrator. The voltage generated by the thermocouple was measured with a digital voltmeter (John Fluke Mfg. Co., model Fluke 77 series II multimeter).

3.4.2 Experimental Procedures

For the thermocouple voltage tests, the temperature of the dry-well temperature calibrator was set to a specific temperature. After the calibrator reached a steady temperature, the tip of the thermocouple was inserted into one of the dry-wells, such that the thermocouple's tip contacted the wall of the dry-well. The voltage generated by the thermocouple was then measured as a function of time using a digital multimeter and a stopwatch. The test was then repeated at other set point temperatures.

In addition to measuring the voltage generated by the thermocouple as a function of time, staff attempted to determine experimentally the temperature at which the electromagnetic gas valve would engage and disengage. Tests were conducted using the dry-well temperature calibrator, set at various temperatures. The thermocouple was attached to the electromagnetic gas valve and the tip of the thermocouple was inserted into one of the dry-wells on the calibrator. The reset button on the gas valve was then pushed in, held for several seconds, and then released. If the valve did not remain open, the sequence was repeated for up to one minute. The set point temperature of the calibrator was then either increased or decreased, to determine the minimum temperature at which the valve would remain open. Once the minimum temperature was determined, the set point temperature was gradually decreased until the gas valve closed (i.e., the electromagnet disengaged).

3.5 Thermoelectric Power Generation Tests

Tests were conducted to determine how much power a thermoelectric generator could generate, if the thermoelectric generator was attached to a tank-top heater.

3.5.1 Thermoelectric Assembly

Staff purchased several thermoelectric modules (model HZ-2) from Hi-Z Technology, Inc. The HZ-2 module is a Bismuth Telluride based semiconductor, consisting of 97 thermocouples, and is capable of generating 2.5 watts at 3.3 volts. Maximum power is obtained when the resistance of the connected load is closely matched to the internal resistance of the module. For the HZ-2, the internal resistance is 4.0 ohms. In addition, maximum power is obtained at the design temperatures, which are 450°F on the hot side and 85°F on the cold side. With no load attached, the maximum voltage is 6.5 volts. The module can operate at a maximum continuous temperature of 480°F and at a maximum intermittent temperature of 750°F. Figure 10 shows a photograph of the HZ-2 module, which is 1.15 inches wide by 1.15 inches high by 0.2 inches thick.

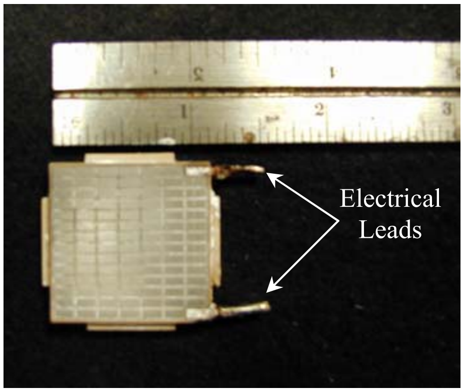


Figure 10. Photograph of the thermoelectric module used in the tests

In order to determine where to mount the thermoelectric module on the heater, staff examined the temperature data from the heater temperature tests. Based on the experimental data, the ideal location appeared to be on the top side of the heat reflector, near the location of thermocouple #5. This location was selected because of the high temperatures that occurred on the heat reflector and because of the flat area on the heat reflector, which was ideal for mounting the thermoelectric assembly. When the heater was operated in a room with a normal oxygen concentration, the steady state temperature at location #5 ranged from approximately 800°F to 860°F, depending on the energy-input rate of the heater. Because the temperature on the heat reflector exceeded the maximum continuous temperature rating for the thermoelectric module (480°F), staff used a mounting bracket to position the module off the surface of the heat reflector. Several different brackets were tested of varying thickness, material, and shape. The mounting bracket was designed to minimize the thermal lag between the heat source and the thermoelectric module. The final design was an L-shaped bracket, fabricated from a 0.25-inch thick piece of aluminum bar stock that was 1.5 inches wide. The base of the bracket, which attached to the heat reflector, was 1.625 inches long. The overall height of the bracket was 2.25 inches.

A heat sink was used to dissipate the heat from the cold side of the thermoelectric module. Figure 11 provides a schematic of the heat sink. The extruded fin heat sink (model EXT-201-E) was purchased from Melcor Corporation. The 4.125" square heat sink is fabricated from aluminum, has 14 fins, and has a thermal resistance (ϕ) of 1.3°C per watt in a natural convection flow. This particular heat sink was selected because it had a relatively low thermal resistance in a natural convective flow, compared to other heat sinks.

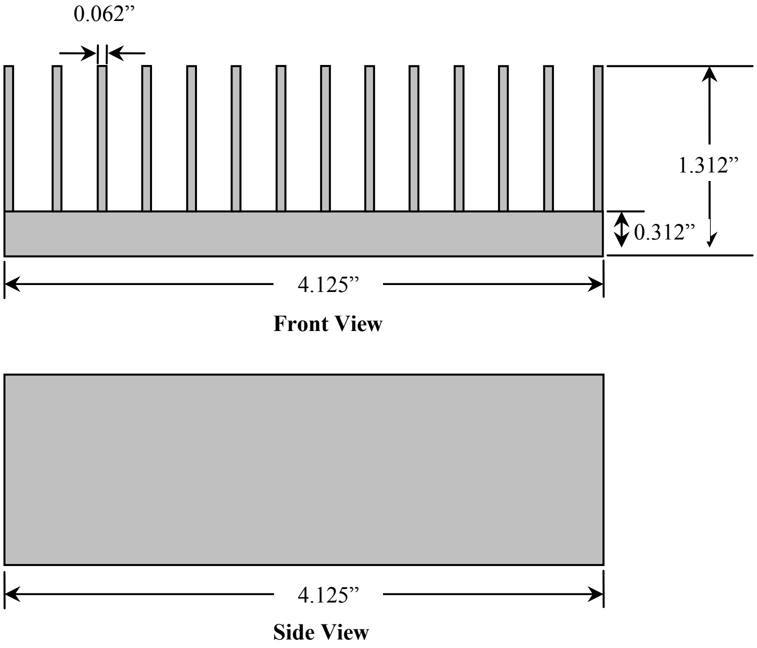
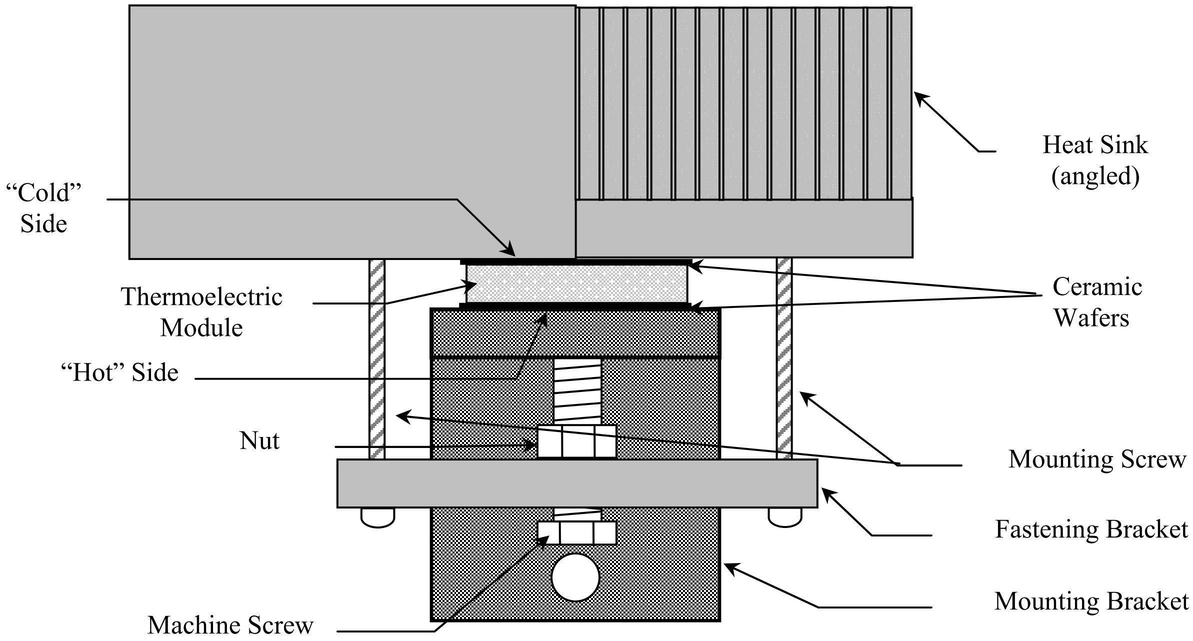


Figure 11. Drawing of heat sink attached to thermoelectric module

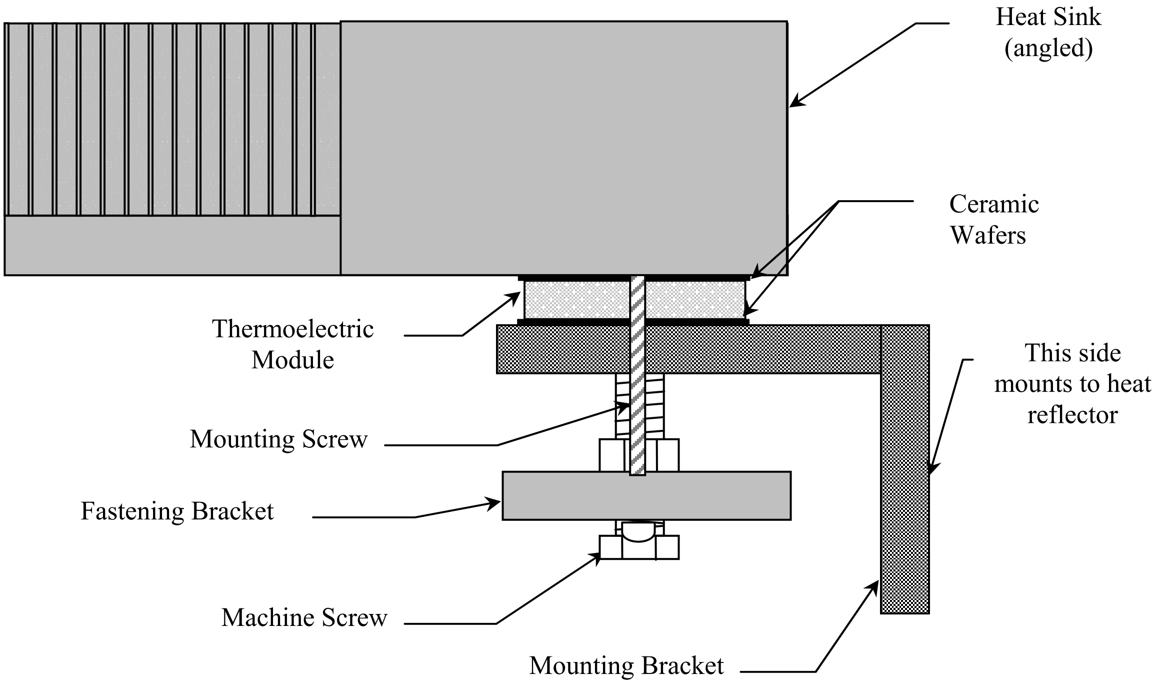
The overall thermoelectric assembly, which included the thermoelectric module, the mounting bracket, and the heat sink, was constructed following the guidelines suggested by Hi-Z Technology (Leavitt *et.al.*, 1996) when possible. Figure 12 is a drawing showing the thermoelectric assembly. One view shows the front of the assembly, while the other view shows the side of the assembly. It should be noted that the heat sink was angled at about a 45-degree angle relative to the mounting bracket, so that the heat sink fins would be vertical when the assembly was mounted on the heat reflector. A vertical fin orientation was selected, because it provided the greatest heat transfer in a natural convection flow.

Because the heat sink and the mounting bracket are metal and can therefore conduct electricity, the thermoelectric module had to be electrically insulated from each of them. Therefore, a 0.01-inch thick ceramic wafer (Hi-Z Technology) was placed on each side of the thermoelectric module. To minimize the thermal resistance at each interface point (e.g., mounting bracket and ceramic wafer, ceramic wafer and module, etc.), a silicon heat transfer compound was used (NFO Technologies, Chemplex 1381).

Screws could not be attached to the mounting bracket to secure the mounting bracket to the heat sink, because the width of the mounting bracket was not much wider than the thermoelectric module (1.50 inches verses 1.15 inches). Therefore, a separate fastening bracket was used to secure the mounting bracket to the heat sink, as shown in Figure 12. To minimize the contact area between the fastening bracket and the mounting bracket, a screw was placed in the middle of the fastening bracket. When the screw was tightened, it applied pressure at the center of the thermoelectric module, minimizing any gaps between the mounting bracket and the thermoelectric module. The overall assembly was secured to the heat reflector using a screw and nut.



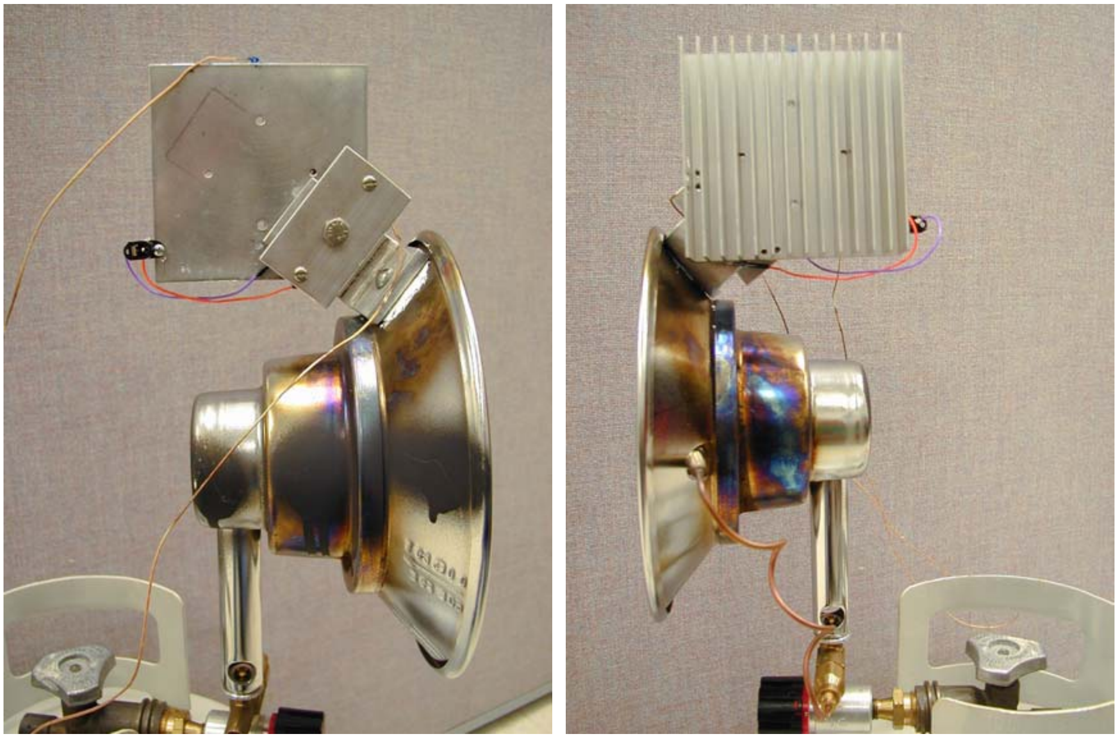
Front View



Side View

Figure 12. Drawing of the thermoelectric assembly

Figure 13 shows the actual thermoelectric assembly attached to a tank-top heater. As the photograph of the heater's right side illustrates, the heat sink fins are vertical. The photograph of the heater's left side shows the location of the mounting bracket and thermoelectric module relative to the heat sink. As previously stated, the length of the mounting bracket was minimized to reduce the thermal lag between the heat source and the thermoelectric module. A short mounting bracket resulted in the placement of the thermoelectric module near the corner of the heat sink.



Heater's Left Side **Heater's Right Side**

Figure 13. Photographs showing the thermoelectric assembly attached to a tank-top heater

Electrical connections were made to the thermoelectric module by soldering a pair of wires to the wire leads on the module. The wires were then connected to a molded coaxial DC power jack, which was fastened to the heat sink. The jack allowed for easy connections with a wire fitted with a DC power connector.

3.5.2 Experimental Setup

The power generated by the thermoelectric module is a function of the load attached to the module and a function of the temperature drop across the module. To create different loads, electrical resistors of known sizes were used. The manufacturer of the thermoelectric module states that maximum power is obtained when the load attached to the module closely matches the internal resistance of the module, which was 4 ohms for this particular thermoelectric module. Therefore, tests were conducted using loads ranging from 0.1 to 20 ohms. Because the power generated by the thermoelectric module is also a function of the temperature drop across the module, tests were conducted by operating the heater in different ambient temperature conditions.

The temperatures on the module's hot side, on the module's cold side, and in the ambient air were measured using K-type thermocouples (Omega, 28-gage). To measure the temperature on the hot side of the module, a small hole was drilled into the side of the mounting bracket and a thermocouple was inserted into the hole. To measure the temperature on the cold side of the module, a small hole was drilled into the side of the heat sink and a thermocouple was inserted into the hole. Both thermocouples were secured in place using high temperature RTV silicon.

A data acquisition system was used to record the voltage generated by the thermoelectric module and the various temperatures. The data acquisition system consisted of a data acquisition board (Data Translation USB Module, Model 9805) that was connected to a computer running a data acquisition program (Labtech Control).

3.5.3 Experimental Procedures

Tests were conducted by operating the heater at its maximum energy-input rate setting in a large open room. A load was attached to the module, and the voltage and temperatures were then allowed to reach steady state. After steady state was achieved, a new load was attached to the module. Data were recorded at a rate of one reading every 30 seconds.

The heater was operated in different ambient air temperatures to determine how the maximum voltage generated by the module varied with temperature. The heater was operated indoors at an ambient temperature of 72ºF and outdoors at an ambient temperature of 26ºF. The maximum voltage occurred with an open circuit; therefore, no load was attached to the thermoelectric module. Only the data acquisition board was attached to the module. Because the data acquisition board had an internal resistance of 100 MΩ, the electrical circuit was in essence equivalent to an open circuit. For these tests, the heater was operated at its maximum energy-input rate setting and the data were recorded at a rate of one reading every 30 seconds. The heater was allowed to reach the ambient temperature before the test proceeded.

3.6 CO Alarm Based Shutoff Tests

One of the CO shutoff systems considered by staff was to use a residential CO alarm in combination with the heater's flame-failure shutoff device (i.e., thermocouple/electromagnetic gas valve). As previously discussed, one manufacturer currently sells such a unit for residential gas appliances. Although not specifically designed for tank-top heaters, it may be possible to adapt the shutoff system for portable heater applications. CPSC staff did not test this particular shutoff system, because the fitting on the heater's thermocouple did not fit the connector that housed the electrical switch on the shutoff system. In addition, CPSC staff wanted to develop a shutoff system that was independent of an external power source, such as batteries, and this particular shutoff system requires 9 volts DC to operate. Although multiple thermoelectric generators could be used to generate 9 volts, CPSC staff decided to design a CO shutoff system using a CO alarm that could be powered using a single thermoelectric generator.

3.6.1 CO Alarm

CPSC staff purchased a couple of residential CO alarms for use in a shutoff system. Staff selected an alarm that required relatively low power to operate (4.5 volts DC, 3 AA batteries). The CO was equipped with an electrochemical sensor and had a digital readout that displayed the CO concentration above 30 ppm. The CO alarm was certified to the Underwriters Laboratory (UL) voluntary standard for CO alarms, *UL Standard 2034*. [8]

In order to use a CO alarm in combination with the heater's flame-failure shutoff device, the CO alarm must be able to produce a signal, such as a voltage, that can be used to trigger or activate the shutoff circuit. Staff initially tried to tap into the circuit for the horn on the CO alarm, because the horn sounds during an alarm situation. However, staff was unsuccessful at obtaining a voltage that was sufficient to power an electronic switch, such as a relay. At the suggestion of another staff member, the circuit for the red light emitting diode (LED) was tapped into, because the red LED flashes during an

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[8] UL Standard 2034 requires that CO alarms comply with the following response times when the alarms are exposed to specified concentrations of CO: at 70 ppm, the unit must alarm within 60-240 minutes; at 150 ppm, the unit must alarm within 10-50 minutes; and at 400 ppm, the unit must alarm within 4-15 minutes.

alarm situation. When the red LED flashed, a voltage of at least 4 volts DC was measured. Four volts is sufficient to power a micro relay.

To verify that tapping into the electrical circuit of the CO alarm did not affect the CO alarm's ability to detect CO, staff conducted alarm tests similar to the ones specified in the UL standard for CO alarms (UL 2034). The two alarms were placed into a 36 cubic foot test chamber located at CPSC. Pure CO was injected into the chamber to obtain a certain steady state CO concentration. UL 2034 specifies that the CO alarms be tested at three specific CO concentrations: 70 ppm, 150 ppm, and 400 ppm. In addition, a test was conducted at 100 ppm, which is the allowable CO concentration in the camp heater standard (ANSI Z21.63). UL 2034 specifies that the gas in the test chamber must reach its steady state value within three minutes. The gas in the test chamber was measured using a CO infrared gas analyzer (Beckman, Model 880A). During a test, the voltage output from the gas analyzer was recorded and the voltage output of each CO alarm was recorded. The data was recorded every 0.1 seconds using a computer controlled data acquisition system that consisted of a data acquisition module (Data Translation Inc., USB Module model 9805), a personnel computer, and a data acquisition program (Labtech Control).

3.6.2 CO Shutoff Circuit

Figure 14 shows a simple shutoff circuit that combines a CO alarm with the heater's flame-failure shutoff device. A normally closed relay is inserted between the thermocouple and the electromagnetic gas valve. The coil in the relay is connected to the alarm circuit of the CO alarm and receives power only when the CO detector alarms. Under normal conditions (i.e., non-hazardous CO levels), the relay is closed and electrical current flows between the thermocouple and the gas valve. When a hazardous CO concentration is detected, the CO detector will alarm, which energizes the coil in the relay. When the coil is energized, the relay opens, interrupting the current flow between the thermocouple and the gas valve, causing the gas valve to close.

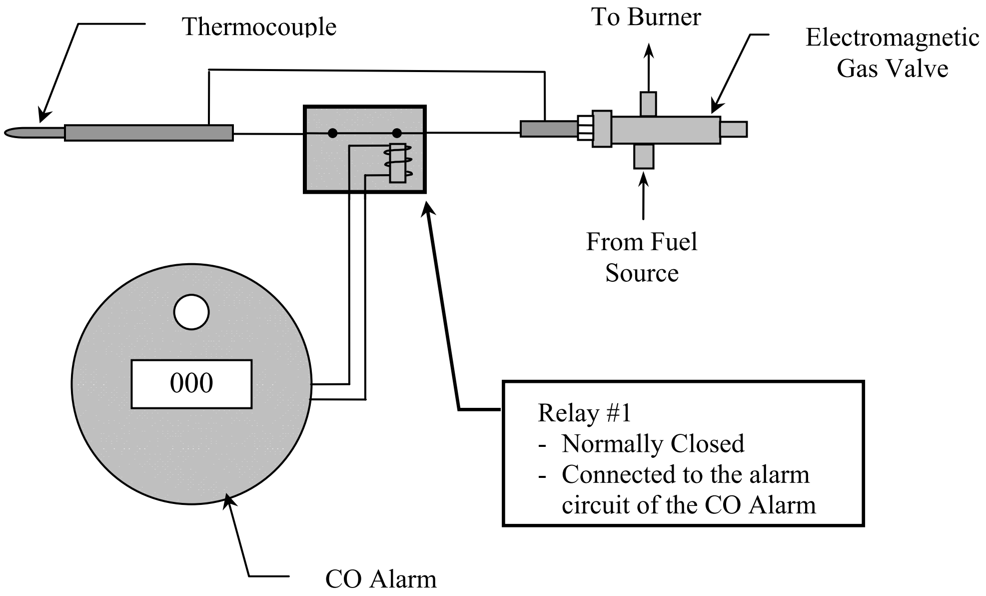

Figure 14 Simple CO shutoff circuit that combines a CO alarm with the heater's flame-failure shutoff device

One problem with the simple shutoff circuit described in Figure 14 is that the heater will still function even if the CO alarm is not working (e.g., no power), because the relay in the shutoff circuit is normally closed. This problem may explain why the CO shutoff device developed by one manufacturer uses a normally open field effect transistor (FET). Without power, the FET (i.e., electrical switch) is normally open. Only when power is supplied to the FET by the CO alarm will the electrical switch close, allowing current to flow between the thermocouple and the electromagnetic gas valve. Instead of using an FET, staff used a second relay to improve the shutoff circuit. The modified shutoff circuit, shown in Figure 15, includes a normally open relay, which is connected to the power supply of the CO alarm. When the CO alarm is powered, the normally open relay closes, allowing current to flow between the thermocouple and the gas valve. When power is removed from the CO alarm, the relay will open, interrupting the current flow between the thermocouple and the gas valve.

Staff assembled the shutoff circuit using electrical components available at a local electronic store. Relay #1 was a single pole, double throw[9], micro relay (Radio Shack, 275-240) that had a nominal coil voltage of 5 volts DC and a coil resistance of 250 ohms. Relay #2 was a single pole, single throw, reed relay (Radio Shack, 275-232) that had a nominal coil voltage of 5 volts DC and a coil resistance of 250 ohms. Both relays had a pick-up voltage (i.e., the minimum voltage to engage the relay) of 3.5 volts DC. To make the electrical connections between the thermocouple, the relays, and the gas valve, the thermocouple was cut in half, near the connector. The outer copper tube was then cut back an additional amount in order to expose the inner wire, and the insulation covering the inner wire was removed. An insulated 22-gauge wire was then attached to the inner copper wire of each half of the thermocouple, and the wires were attached to the appropriate relays. Similarly, an insulated 22-gauge wire was attached to each section of the outer copper tube, connecting them electrically.

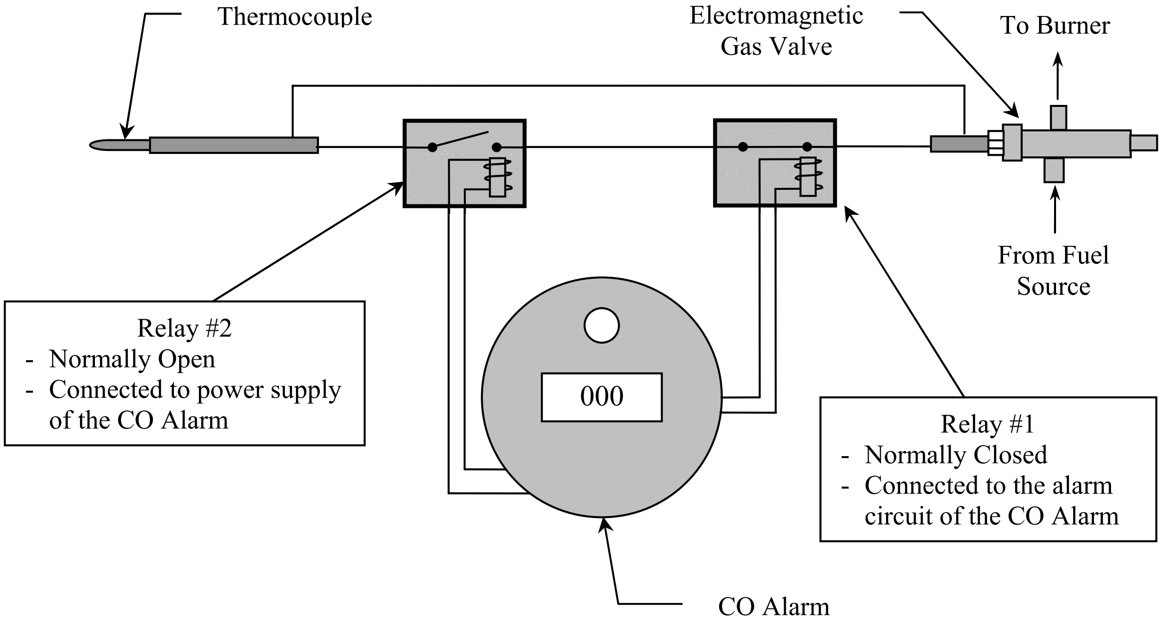

Figure 15. Modified shutoff circuit that adds a relay to verify that sufficient power is being supplied to the CO alarm

If the CO alarm is powered using a thermoelectric generator, there will be a time lag between when the heater starts and when the thermoelectric generator produces sufficient power to close relay #2. Relay #2 needs to be closed in order to allow the current from the thermocouple to energize the electromagnet in the safety valve. Preliminary tests indicated that it would take approximately 2.5 minutes for the thermoelectric generator to produce the 3 volts required to open relay #2. Because this would be a long time to depress the manual rest button on the electromagnetic gas valve, a mechanical timer relay (relay #3) was added to the shutoff circuit, which was used to bypass relay #2 during the startup of the heater. Figure 16 shows the revised shutoff circuit. Relay #3 relay was a single pole, single

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[9] A double throw relay was not required for this application. However, this was the only normally closed, low voltage relay available at the local electronics shop.

throw, spring-wound, mechanical timer (Intermatic, Inc., model FF15MC) that could be adjusted up to 15 minutes.

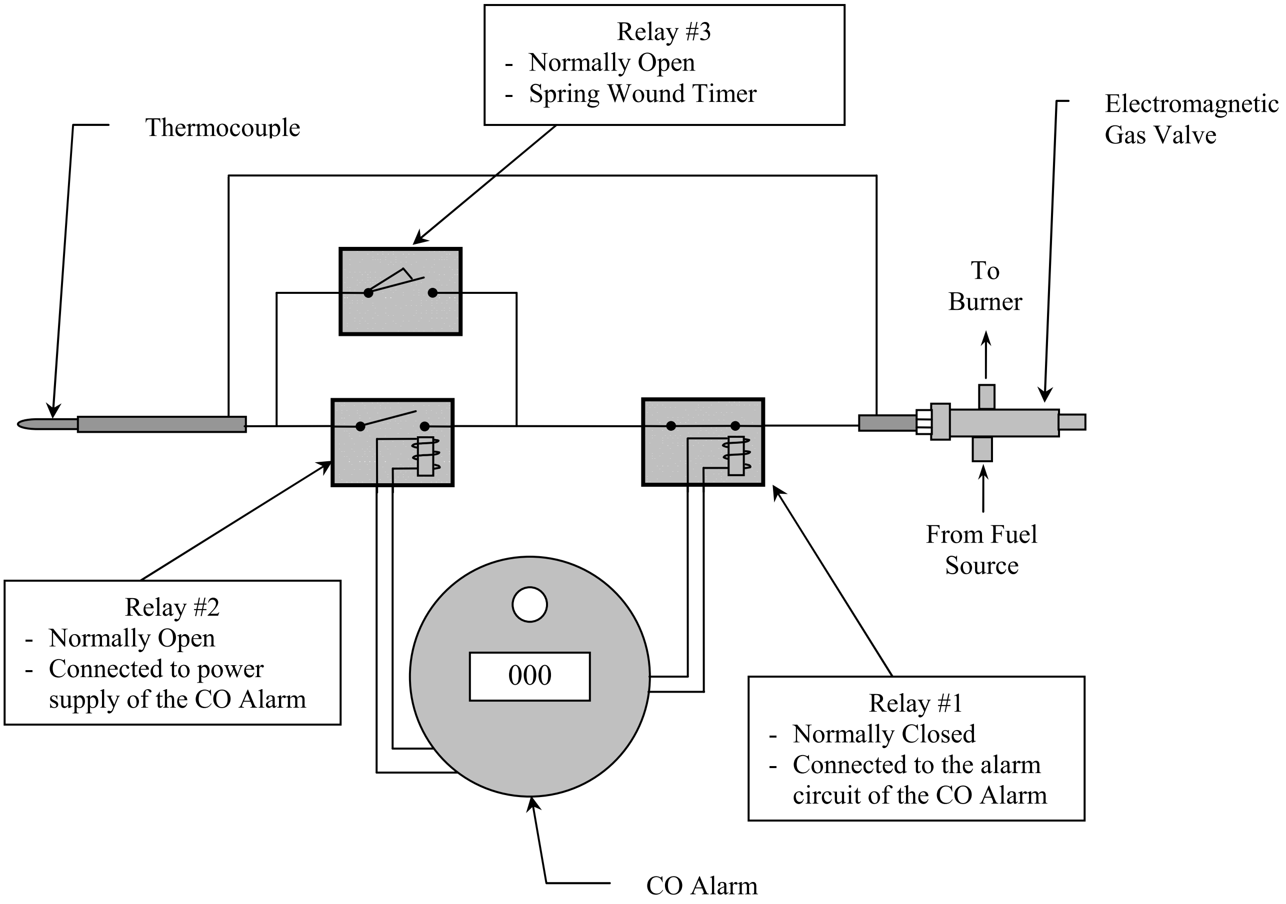

Figure 16. CO shutoff circuit required when a thermoelectric generator supplies the power for the CO alarm

3.6.3 Shutoff Tests

The shutoff tests were conducted similar to the oxygen depletion tests. The CO shutoff system was connected to a tank-top heater, which was equipped with a thermoelectric generator to power the shutoff system. The heater was operated in the 100 cubic foot test chamber at reduced oxygen concentrations. The air exchange rate was set so that the oxygen was depleted to an O_2 concentration just prior to the flame self-extinguishing. Tests were conducted with the heater operating at its maximum energy-input rate and at its minimum energy-input rate. In addition to the data collected during the normal oxygen depletion tests, the following data was also recorded: voltage generated by thermoelectric module, the temperature on the hot side of the module, and the temperature on the cold side of the module.

4. DATA REDUCTION

4.1 Energy Input Rate

The energy-input rate of the heater, Q, was calculated indirectly from the mass of propane consumed by the heater over time. The energy-input rate was calculated as follows:

$$Q = \frac{C_1 HHV}{\rho} \frac{\Delta m}{\Delta t} \tag{1}$$

In Equation 1, C_1 is a conversion constant, *HHV* is the heating value of propane gas, ρ is the density of the propane gas, and Δm is the mass of propane fuel consumed during the time interval Δt. A HHV of 2,500 Btu/ft^3 was assumed for propane gas. The density of the propane gas used in the calculation was 0.114 lb_m/ft^3, and the density is based on a temperature of 70°F and a pressure of 14.7 lb_f/in^2.

4.2 Air Exchange Rate

The equation describing the air exchange rate in the chamber can be derived from a simple mass balance of SF_6 in the chamber. The decay of SF_6 with time can be described by Equation 2:

$$C_t = C_o\, e^{-kt} \tag{2}$$

In Equation 2, C_t is the concentration of SF_6 at time t, C_o is the initial concentration of SF_6 at the start of the decay, k is the air exchange rate, and t is time. Equation 2 was derived based on the following assumptions: the air in the chamber is well mixed, the SF_6 does not get absorbed inside the chamber, and the background concentration of SF_6 is zero. Equation 2 can be rearranged to solve for the quantity (kt) as follows:

$$\mathrm{Ln}\,(C_t/C_o) = -k\,t \tag{3}$$

Equation 3 indicates that a plot of the quantity $\mathrm{Ln}\,(C_t/C_o)$ versus time should be linear with time and that the air exchange rate (k) will be equal to the slope of this line. Since the line should be linear, linear regression can be used to fit a line to the data. An expression describing how well the line fits the data is the R^2 term, where R is the correlation coefficient. An R^2 value of 1.0 indicates that the line obtained by linear regression fits the data perfectly. For each test, a linear regression was performed on the SF_6 decay data and the air exchange rate was obtained from the slope of this line. The test was acceptable if the R^2 term was greater than 0.9.

4.3 CO Generation Rate

The rate at which the heater generated CO can be derived from a simple mass balance of CO in the chamber. Between any two time intervals (t_i and t_{i+1}), the source strength can be calculated from the following equation,

$$S_{t_{i+1}} = \frac{Vk\left[C_{t_{i+1}} - C_{t_i} e^{-k\left(t_{i+1} - t_i\right)}\right]}{\left[1 - e^{-k\left(t_{i+1} - t_i\right)}\right]} \tag{4}$$

In Equation 4, $S_{t\,i+1}$ is the generation rate of CO at time t_{i+1}, V is the volume of the chamber, k is the air exchange rate, $C_{t\,i+1}$ is the concentration of CO at time t_{i+1}, and $C_{t\,i}$ is the concentration of CO at time t_i. Equation 4 was derived based on assuming that the air in the chamber is well mixed and that the CO is not absorbed inside the chamber.

5. RESULTS

5.1 Oxygen Depletion Tests

Tests were conducted with a tank-top heater operating in a room with a depleted supply of oxygen to determine what effect the oxygen concentration had on the products of combustion and the flame.

5.1.1 Products of Combustion

When the propane heater is operated in a large open area having a normal supply of oxygen, the main products of combustion are carbon dioxide (CO_2) and water vapor (H_2O), with trace amounts of other chemical species present, such as CO. In the ideal case of perfect combustion, for every 1 cubic foot of gaseous propane burned, 3 cubic feet of CO_2 are produced and 4 cubic feet of H_2O are produced.

Figure 17 illustrates how the concentrations of CO, CO_2, O_2, and HC in the chamber varied with time, when Heater A was operated at its maximum energy-input rate (~13,000 Btu/hr) in an oxygen depleted environment. The air exchange was approximately 3 ACH through the 100 cubic foot test chamber. At these operating conditions, the oxygen concentration was depleted from a normal room concentration of approximately 20.9 percent to a steady-state concentration of 12.9 percent. The CO concentration in the room increased from zero to a steady state concentration of 972 ppm. The CO_2 reached a steady state concentration of 5.2 percent and the HC concentration peaked at approximately 3 percent of the lower explosive limit (LEL) for propane.[10]

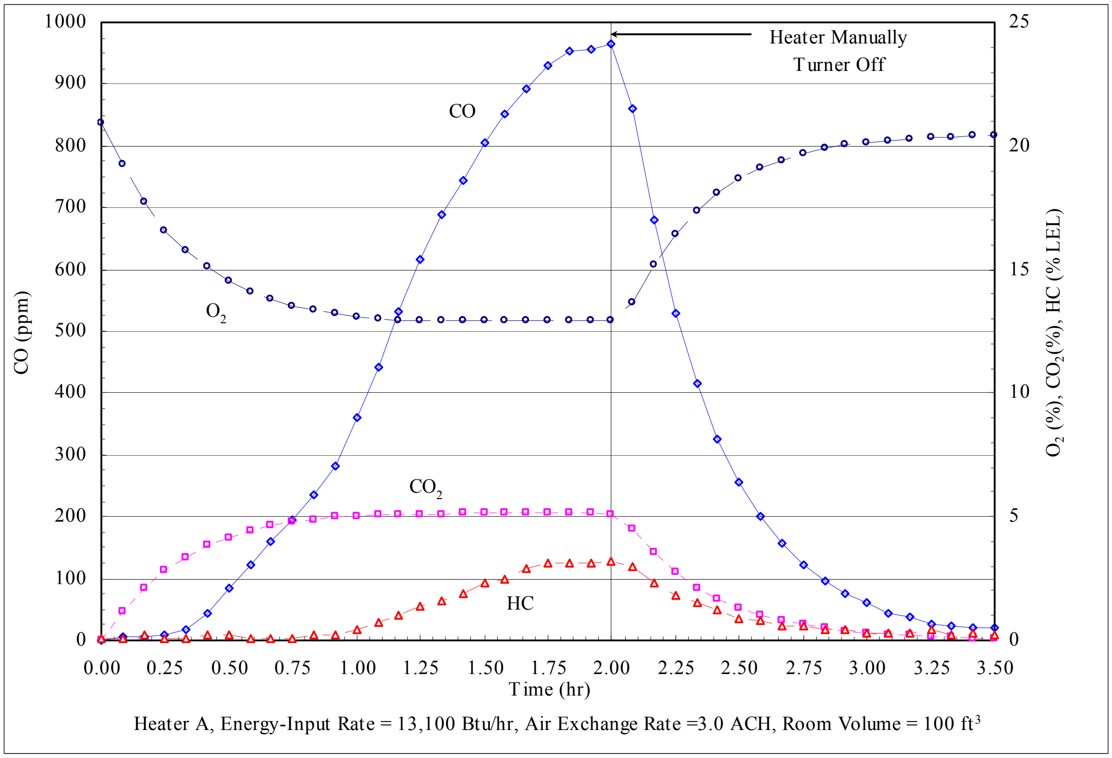

Figure 17. Concentrations of CO, O_2, CO_2, and HC as a function of time, when Heater A was operated at its maximum energy-input rate in a 100 ft^3 room with an air exchange rate of 3.0 ACH

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[10] LEL is the minimum concentration of fuel required for combustion with air. At 100 percent LEL, combustion is possible. For propane, the LEL is 2.1 percent propane in air.

Figure 18 illustrates how the concentrations of CO, CO_2, O_2, and HC in the chamber varied with time, when Heater A was operated at its minimum energy-input rate (~10,600 Btu/hr) and the air exchange rate was approximately 2.5 ACH. At these operating conditions, the oxygen concentration was depleted from a normal room concentration of approximately 20.9 percent to a steady-state concentration of 12.9 percent. The CO concentration in the room increased from zero to a steady state concentration of 989 ppm. The CO_2 reached a steady state concentration of 5.1 percent and the HC concentration peaked at approximately 1 percent LEL.

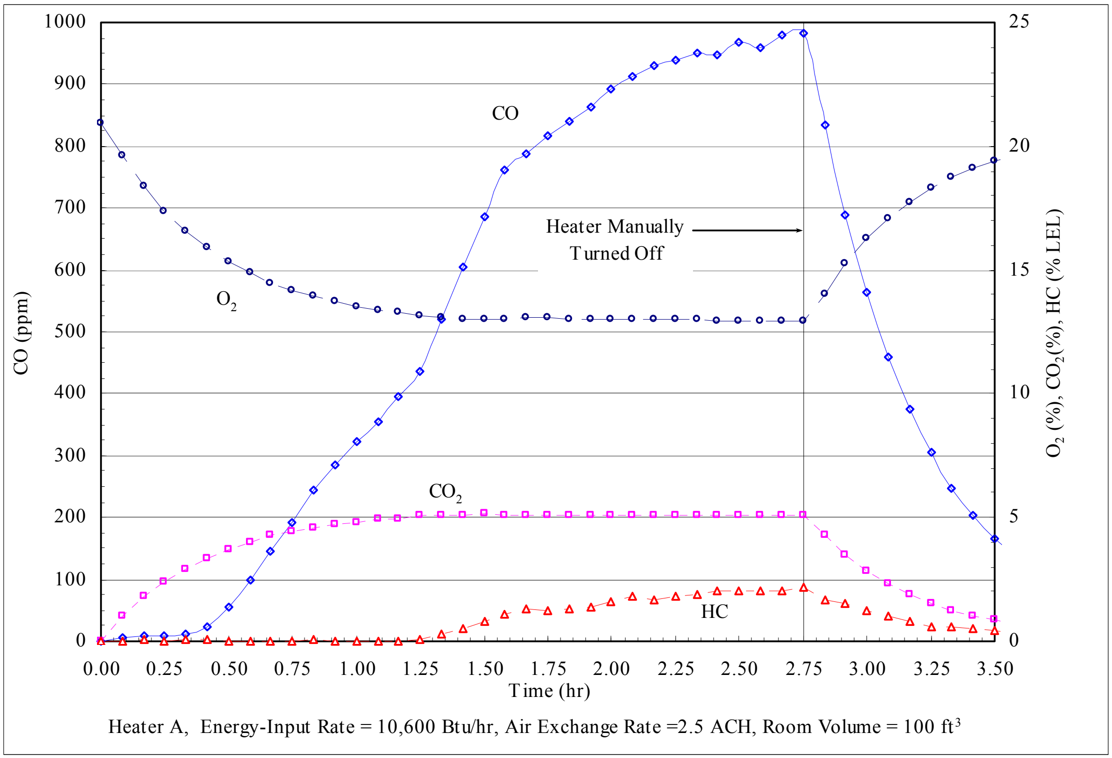


Figure 18. Concentrations of CO, O_2, CO_2, and HC as a function of time, when Heater A operating at its minimum energy-input rate in a 100 ft^3 room with an air exchange rate of 2.5 ACH

The data shown in Figures 17 and 18 were obtained with Heater A. Similar results were obtained with Heaters B and C. A summary of the test results is located in Appendix A. Because staff was primarily interested in the relationship between the amount of CO produced by the heater as a function of the O_2 concentration, tests were only conducted at air exchange rates that would result in the maximum depletion of the oxygen without extinguishing the flame. Tests at a particular energy-input rate setting often had to be repeated, in order to find this minimum O_2 concentration. In general, the test samples could operate at O_2 concentration down to approximately 13 percent.

The gas concentrations presented in Figures 17 and 18 are plotted against time, which is a function of the room size and the air exchange rate. If the room size is changed or the air exchange rate is changed, the concentration of the various gases will change, in addition to the time required to reach steady state conditions. Therefore, to remove the effect of time, the concentrations of CO, CO_2, and HC were plotted against the O_2 concentration. Figure 19 illustrates how the CO concentration in the room varied with the O_2 concentration, when the heater was operated at either its maximum or minimum energy-input rate. The CO concentration increased in an exponential manner, when the O_2 concentration was depleted below approximately 16 percent. In addition, the CO concentration was found to increase at a slightly faster rate, when the heater was operated at its minimum energy-input rate setting. It should be noted that Figure 19 is a plot of transient CO concentrations, which are not necessarily equivalent to the steady state concentrations that would be obtained at a particular O_2 concentration.

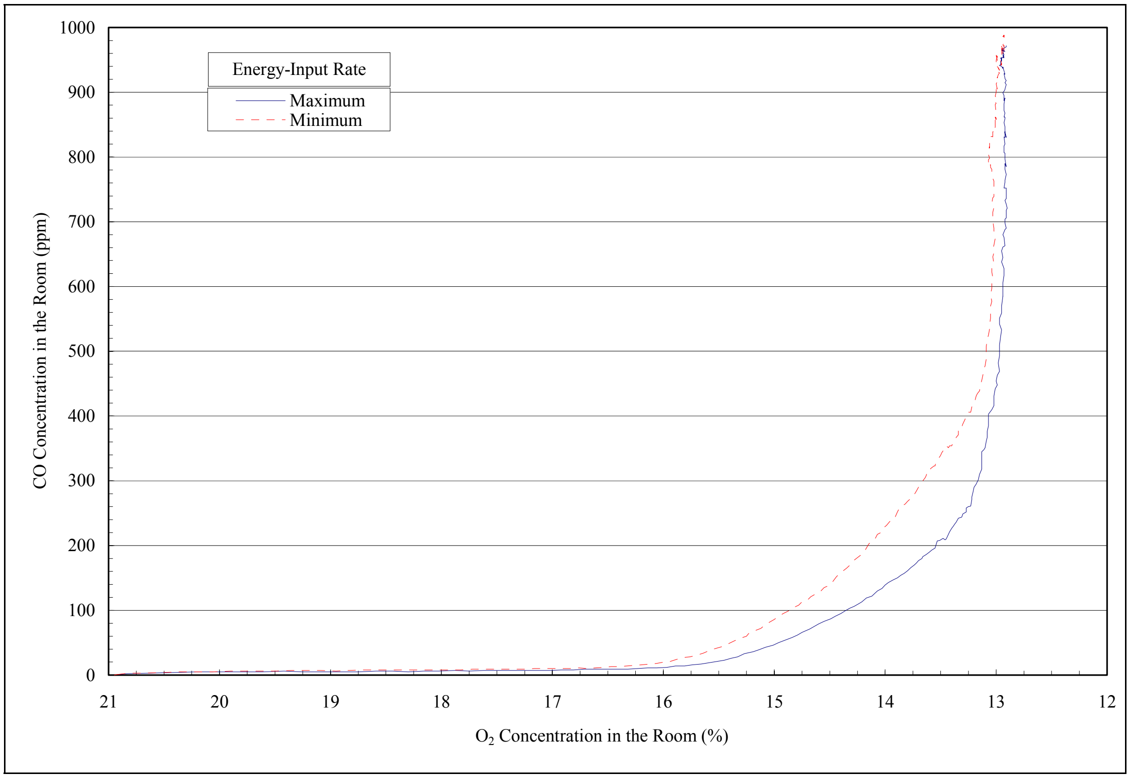


Figure 19. CO concentration as a function of the O_2 concentration (Heater A)

Figure 20 illustrates how the CO generation rate of the heater is a function of the O_2 concentration in the room. The CO generation rate of the heater is minimal until the O_2 concentration is depleted below approximately 16 percent. The CO generation rate then begins to increase steadily until the oxygen concentration is depleted below approximately 13.2 percent. Between 13.2 and 12.9 percent O_2, the CO generation rate approximately doubles. As Figure 20 illustrates, there is a slight increase in the rate of CO generation between 16.5 percent O_2 and 13.2 percent O_2, when operating the heater at its minimum energy-input rate compared to operating the heater at its maximum energy-input rate.

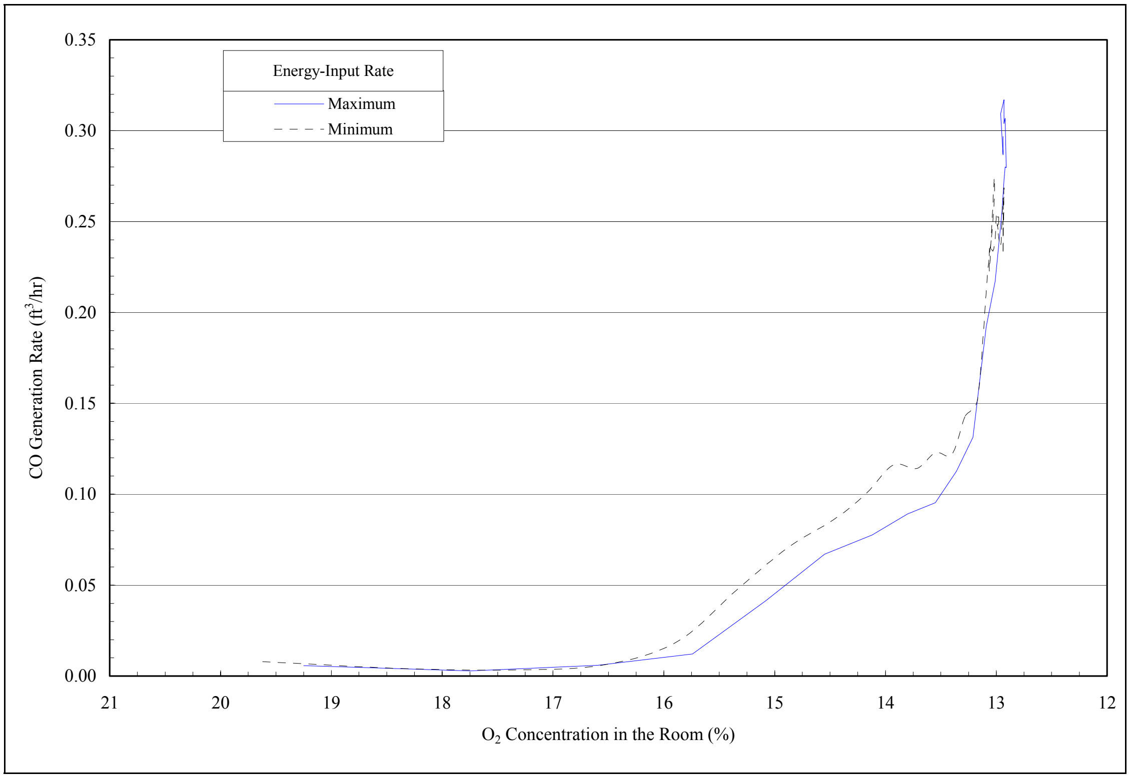
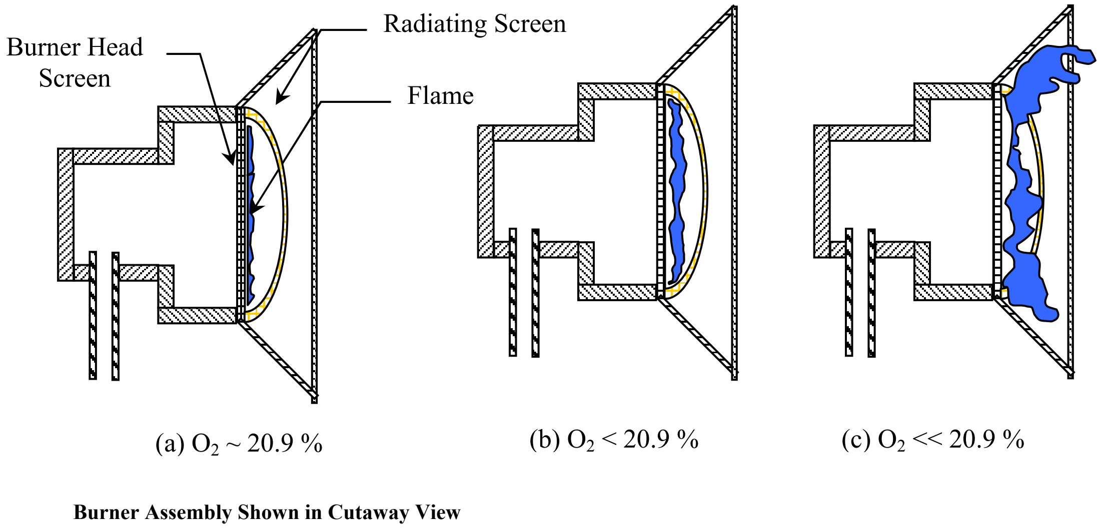


Figure 20. Rate of CO generated by Heater A as a function of the O_2 concentration in the room.

5.1.2 Flame Appearance

When the heater is operated in a room having a normal supply of oxygen (i.e., ~ 20.9 % O_2), a thin blue flame will burn at the surface of the burner, as illustrated in Figure 21 (a). As the oxygen in the room is depleted, the burning velocity of the flame decreases, causing the flame to burn farther away from the burner (i.e., flame lifting occurs), as illustrated in Figure 21 (b). As the oxygen in the room is further depleted, flame lifting continues and the flame begins to elongate, extending past the primary radiating screen, as shown in Figure 21 (c). At a certain O_2 concentration, the burning velocity will be too low, and the flame will lift off the burner completely, causing the flame to self extinguish.



(a) O_2 ~ 20.9 %

(b) O_2 < 20.9 %

(c) O_2 << 20.9 %

Burner Assembly Shown in Cutaway View

Figure 21. Drawing illustrating the flame on the radiant burner at three different O_2 concentrations

Figure 22 is a series of photographs that show the appearance of the burner and the flame at different oxygen concentrations when Heater A was operated at its maximum energy-input rate and at its minimum energy-input rate. The thin blue flame near the surface of the burner cannot be seen at oxygen concentrations greater than 16 percent, due to the incandescent glow of the primary radiating screen. As the oxygen was depleted below 16 percent, flame lifting was observed near the top of the burner when the heater was operated at its maximum energy-input rate. When the heater was operated at its minimum energy-input rate, flame lifting occurred between 15 and 16 percent O_2, with the flame extending past the main radiating screen. At approximately 14 percent O_2, flame lifting was observed near the bottom of the burner.

Max Btu/hr Min Btu/hr
18% O_2

Max Btu/hr Min Btu/hr
17% O_2

Max Btu/hr Min Btu/hr
16% O_2

Max Btu/hr Min Btu/hr
15% O_2

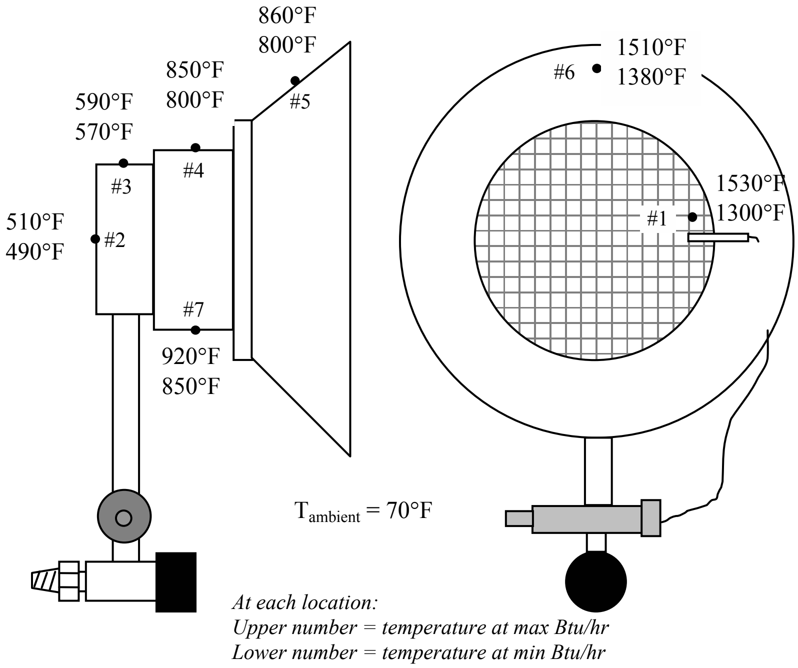
Max Btu/hr Min Btu/hr
14% O_2

Max Btu/hr Min Btu/hr
13% O_2

Figure 22. Photographs that show the appearance of the burner and the flame at different O_2 concentrations when Heater A was operated at its maximum energy-input rate (Max Btu/hr) and its minimum energy-input rate (Min Btu/hr).

5.2 Heater Temperature Tests

To establish the baseline temperatures at each location under normal oxygen conditions, the heater was operated in a large room having a normal O_2 concentration (~20.9 percent). Figure 23 is a drawing of the heater showing the steady state temperatures at each location. In the figure, two numbers are shown at each measurement location; the upper number represents the temperature that occurred when the heater was operated at its maximum energy-input rate, and the lower number represents the temperature when the heater was operated at its minimum energy-input rate. The temperature at each location decreased by approximately 3 to 15 percent when the heater was operated at its minimum energy-input rate compared to when the heater was operated at its maximum energy-input rate. As expected, the maximum temperatures occurred at location #1 (in front of the burner) and location #6 (above the burner), because the hot gases from the burner flowed directly over these thermocouples. The air temperature at location #1 and #6 ranged from 1300°F to 1530°F. The temperatures on the surface of the heater ranged from 490°F to 920°F.



At each location:
Upper number = temperature at max Btu/hr
Lower number = temperature at min Btu/hr

Figure 23. Average steady state temperatures at various locations on and near the heater when the heater was operated in a large room with a normal oxygen concentration

Figures 24 and 25 illustrate how the temperature at each location varied with time, when the heater was operated at its maximum energy-input rate and its minimum energy-input rate, respectively, in a room that had a normal oxygen concentration (~20.9 percent). In both situations, the two thermocouples that measured the air temperature (#1 and #6) reached steady state within approximately 3 minutes after the heater was turned on, and the five thermocouples that measured the surface temperature on the heater (#2, #3, #4, #5, and #7) achieved steady state within approximately 7 minutes.

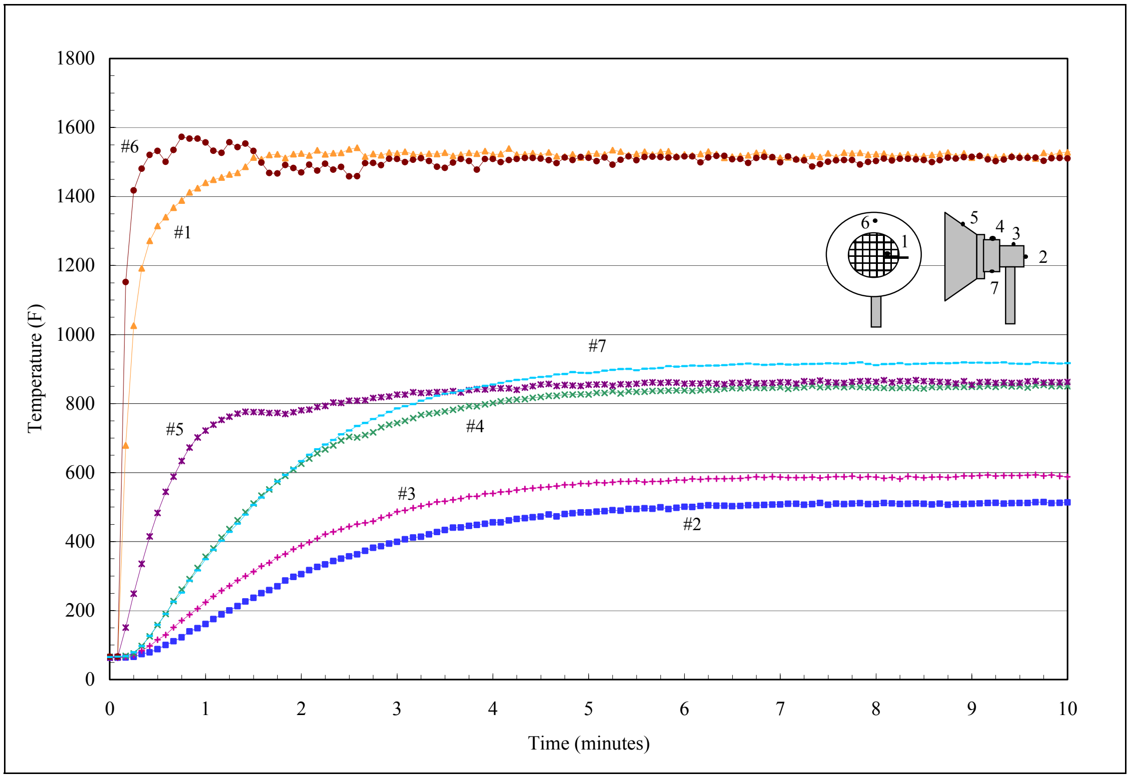


Figure 24. Temperatures measured at different locations (#1 - 7) on the heater and near the heater as a function of time; the heater was operated at its maximum energy-input rate in a room having a normal oxygen concentration

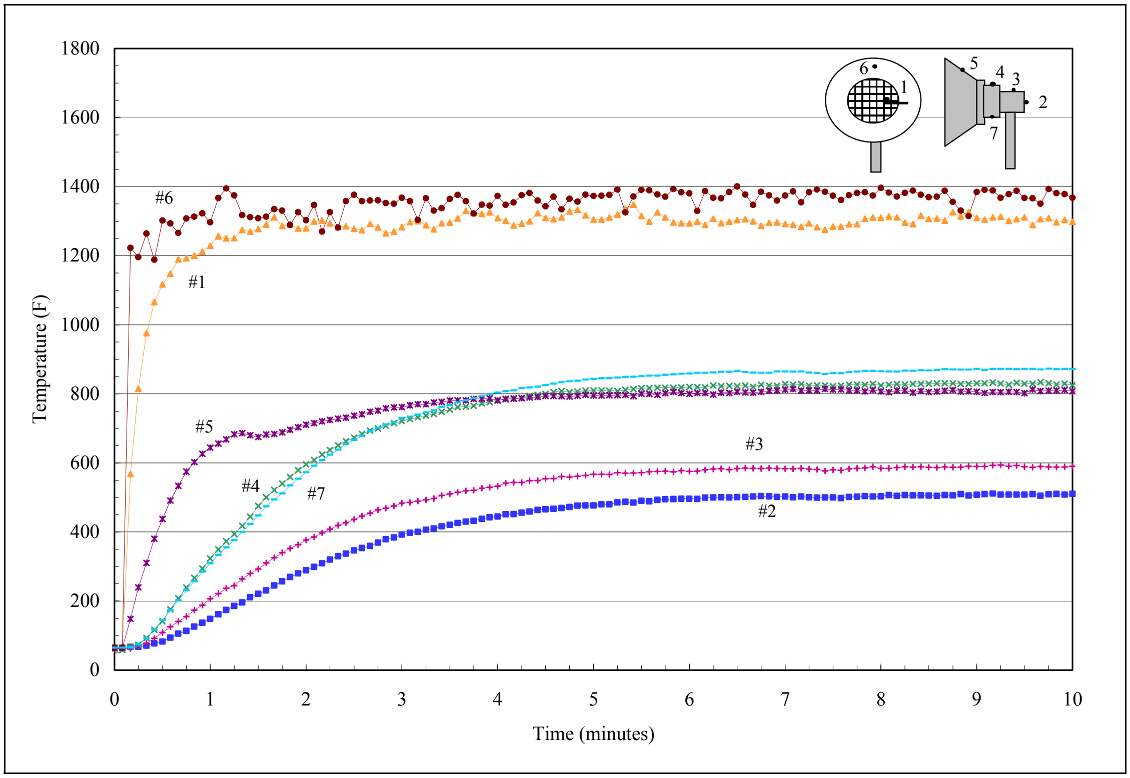


Figure 25. Temperatures measured at different locations (#1 - 7) on the heater and near the heater as a function of time; the heater was operated at its minimum energy-input rate in a room with a normal oxygen concentration

Figure 26 illustrates how the temperature at each thermocouple location varied with the oxygen concentration, when the heater was operated at its maximum energy-input rate in the 100 cubic foot test chamber. The air exchange rate through the test chamber was adjusted so that the oxygen would be depleted during the test. The graph can be divided into several different regions, based on if the temperatures are increasing or decreasing at a given O_2 concentration. Between an O_2 concentration of 20.9 percent and approximately 18.8 percent, all of the temperatures increase and then level off as the heater warms up. Between an O_2 concentration of approximately 18.8 percent and 17.8 percent, the surface temperatures on the body of the heater (#2, #3, #4, and #7) all start to slowly decrease, while the surface temperature on the heat reflector (#5) and the air temperatures in front of the burner (#1) and above the burner (#6) remain somewhat constant. Between an O_2 concentration of approximately 17.8 percent and 16.4 percent, the surface temperatures on the body of the heater decrease at a slightly quicker rate, while the temperature on the heat reflector starts to increase. During this same period, the air temperature in front of the burner starts to decrease, while the air temperature above the burner starts to increase. Below an O_2 concentration of approximately 16.4 percent, the surface temperatures on the body of the heater decrease at a quicker rate, while the air temperature in front of the burner continues to decrease and the air temperature above the burner continues to increase. Below 16.4 percent O_2, the surface temperature on the heat reflector leveled off until the O_2 concentration was depleted to approximately 15.6 percent, at which point the temperature started to decrease. The CO concentration started to increase rapidly when the O_2 concentration was depleted below approximately 16.4 percent.

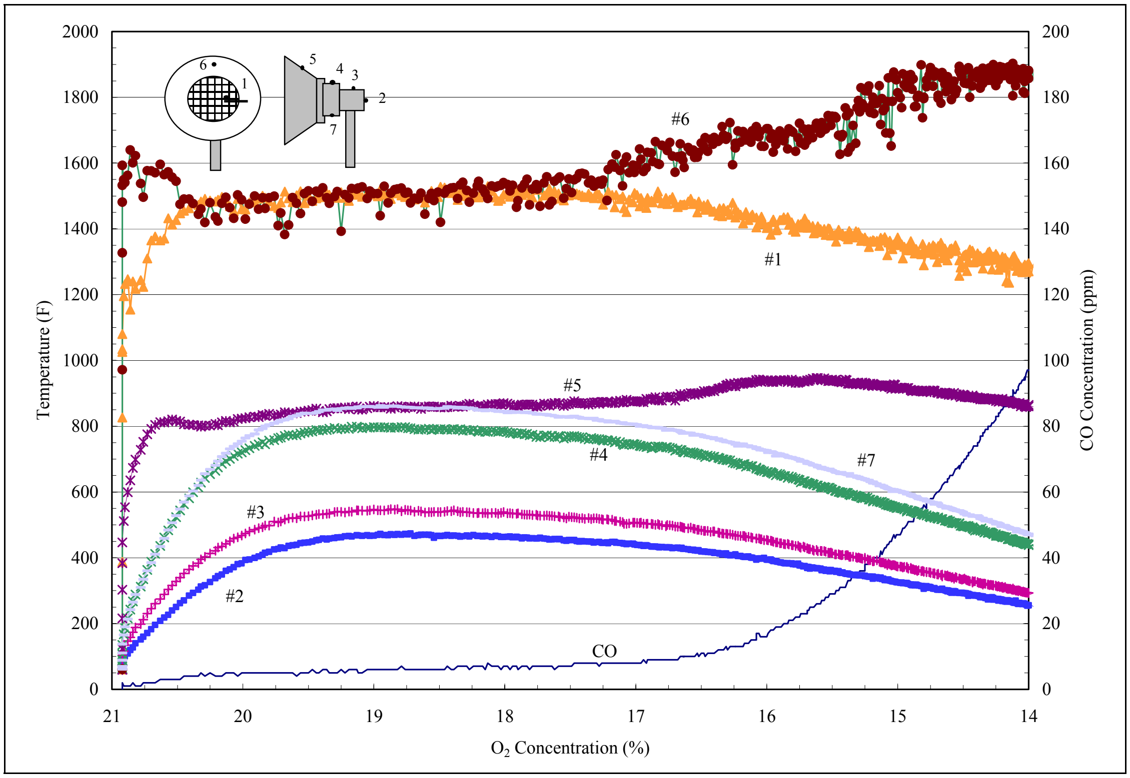


Figure 26. Temperatures on the heater and near the heater as a function of the oxygen concentration in the room; the heater was operated at its maximum energy-input rate in a confined space

Figure 27 illustrates how the temperature at each location varied with the oxygen concentration, when the heater was operated in an oxygen-depleted environment at its minimum energy-input rate. Between an O_2 concentration of 20.9 percent and approximately 18.5 percent, all of the temperatures increase and then level off as the heater warms up. Between an O_2 concentration of approximately 18.5 percent and 15.9 percent, the surface temperatures on the body of the heater (#2, #3, #4, and #7) all start to slowly decrease, while the surface temperature on the heat reflector (#5) and the air temperatures in front of the burner (#1) and above the burner (#6) remain fairly constant. Below an O_2 concentration of approximately 15.9 percent, the surface temperatures on the body of the heater decrease at a quicker rate, while the air temperature in front of the burner starts to decrease and the air temperature above the burner starts to increase. Below 15.9 percent O_2, the surface temperature on the heat reflector increased until the O_2 concentration was depleted to approximately 15.4 percent, at which point the temperature leveled off. The CO concentration started to increase rapidly when the O_2 concentration was depleted below approximately 17 percent.

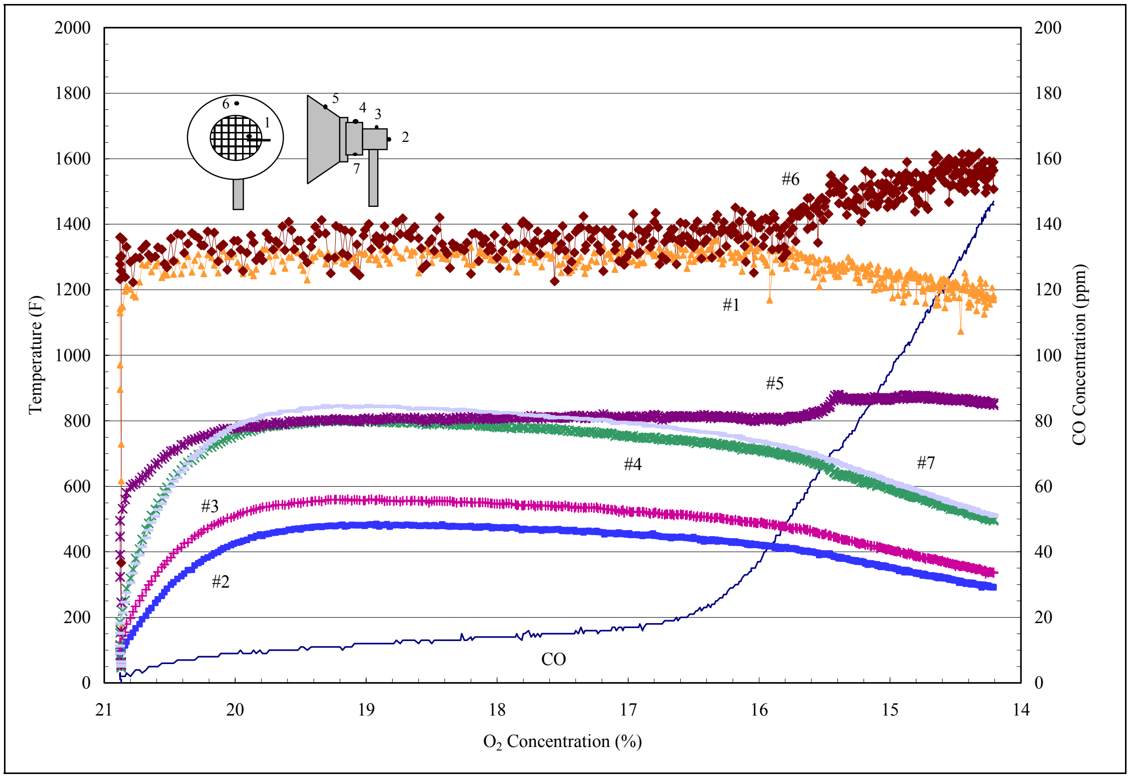


Figure 27. Temperatures on and near the heater as a function of the oxygen concentration in the room; the heater was operated at its minimum energy-input rate in a confined space

Figures 28 and 29 re-plot the temperature data in Figures 26 and 27, respectively, in terms of a temperature difference between the temperature obtained at an O_2 concentration of 19 percent and the corresponding temperature at O_2 concentrations less than 19 percent. An O_2 concentration of 19 percent was selected as the reference point, because the temperatures all appeared to have reached steady state by an O_2 concentration of 19 percent.

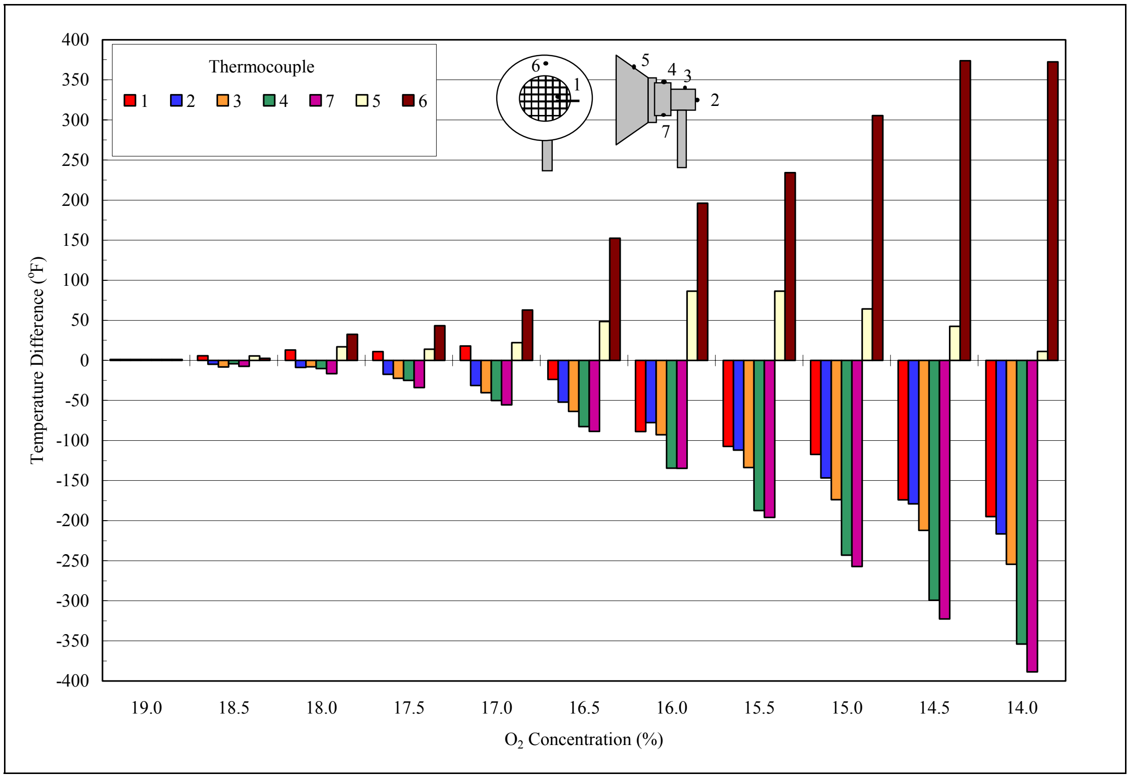


Figure 28. Temperature difference between the temperatures obtained at an O_2 concentration of 19 percent and the corresponding temperatures at O_2 concentrations less than 19 percent; the heater was operated at its maximum energy-input rate in a poorly ventilated confined space

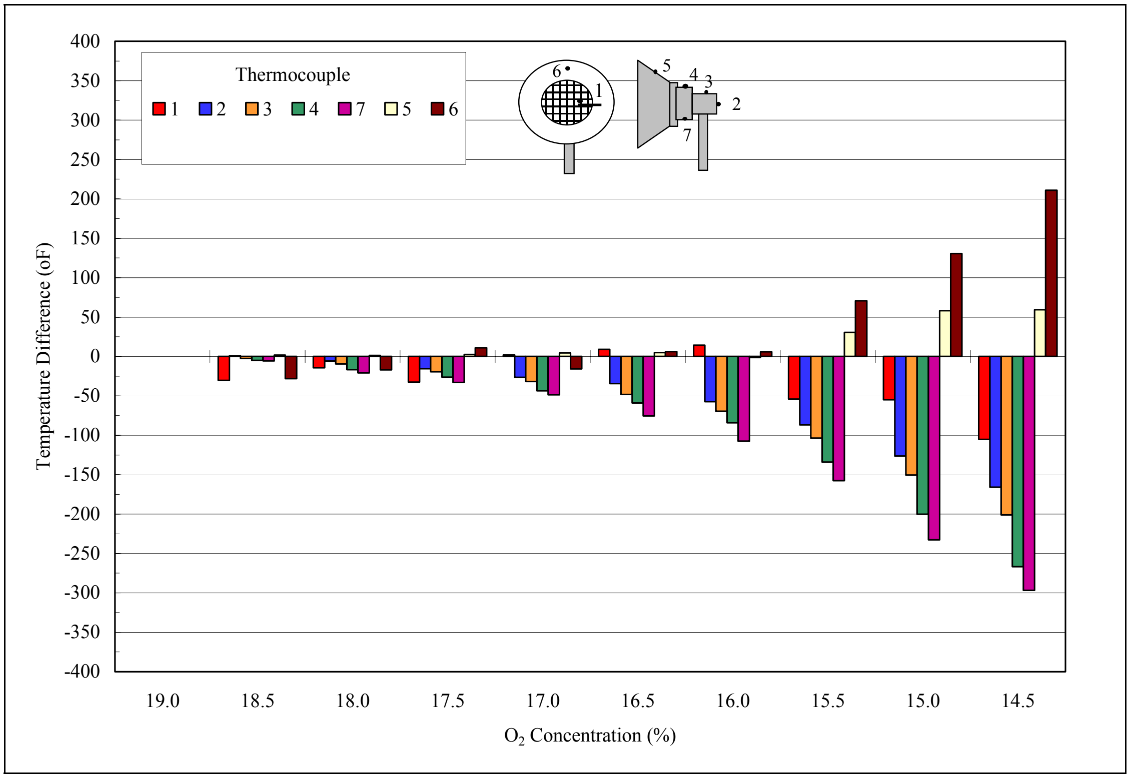


Figure 29. Temperature difference between the temperatures obtained at an O_2 concentration of 19 percent and the corresponding temperatures at O_2 concentrations less than 19 percent; the heater was operated at its minimum energy-input rate in a poorly ventilated confined space

5.3 Thermocouple Tests

Figure 30 illustrates how the voltage generated by a rod-and-tube type thermocouple, which is currently in use on the sample tank-top heaters, varies with time and set point temperatures. For a given set point temperature, the peak voltage occurred at approximately 20 seconds after heat was applied to the thermocouple. The voltage then decreased to its steady state temperature within approximately 5 minutes. The steady state voltages were approximately 60 to 75 percent of the peak voltages.

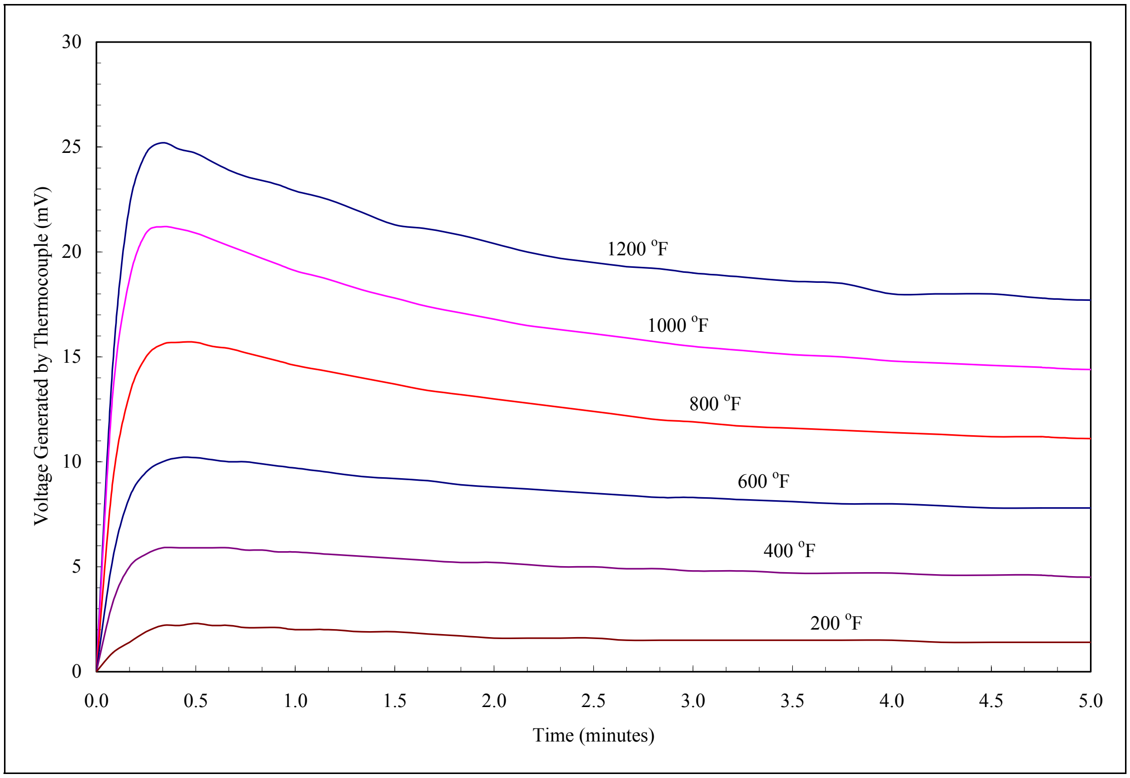


Figure 30. Voltage generated by the tank-top heater's rod-and-tube type thermocouple as a function of time and set point temperatures

Figure 31 re-plots the voltage data in Figure 30 as a function temperature, for different time intervals. For clarity purposes, only two curves are shown in Figure 31. The two curves illustrate how the voltage generated by the thermocouple decreases over time as the cold junction heats up.

Staff obtained mixed results when trying to determine the temperatures at which the electromagnetic gas valve would engage and disengage. Staff first tried to determine the temperatures through experimental tests by placing the thermocouple in the dry-well thermocouple. The positioning of the thermocouple in the thermocouple calibrator affected the tests results. The temperature at which the electromagnetic gas valve would engage ranged from approximately 300°F to 525°F, and the valve disengaged at a temperature of approximately 250°F.

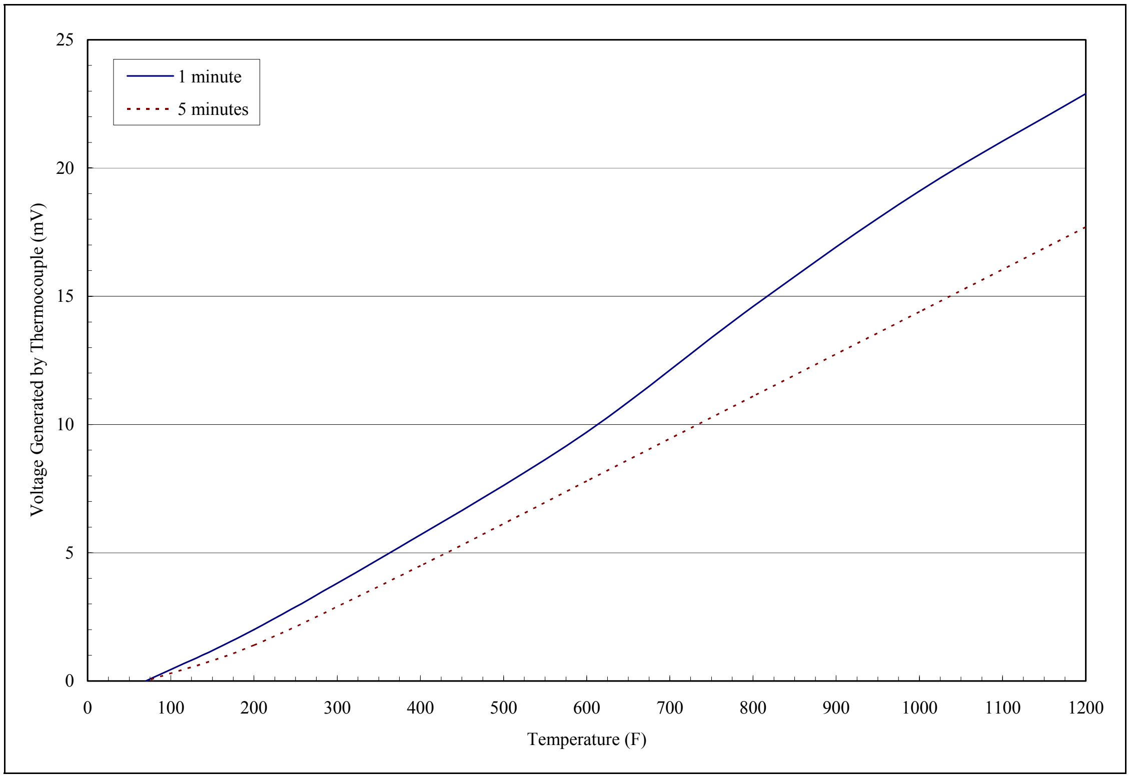


Figure 31. Voltage generated by the tank-top heater's thermocouple as a function of temperature, at different time intervals

Staff then tried to calculate the temperatures at which the electromagnetic gas valve would engage and disengage, based on general data obtained from the manufacturer of the thermocouple and gas valve. The electromagnetic gas valve is rated based on the engaging strength and the disengaging strength, which is given in terms of electrical current. For this particular valve manufacturer, the maximum engaging strength is typically 80 to 240 mA, and the minimum disengaging strength is typically 10 to 110 mA. The voltage that corresponds to the particular current can be calculated using Ohm's Law (voltage = current x resistance), if the resistance of the electrical circuit is known. A closed loop electrical circuit is formed when the thermocouple is attached to the gas valve. The resistance of the circuit includes such things as the resistance of the thermocouple, the electromagnet, and the connection contact. Based on information from the manufacturer, the thermocouple resistance was estimated as 15 mΩ, and the electrical resistance of the electromagnet was assumed to be 20 mΩ. Neglecting all other types of resistances, the total resistance was assumed to be 35 mΩ. Therefore, using Ohm's Law, the voltage required to engage the electromagnet at a current that ranged from 80 to 240 mA would be 2.8 to 8.4 mV. The voltage required to disengage the electromagnet at a current that ranged 10 to 110 mA would be 0.35 to 3.8 mV. Based on the experimental data for the voltage at different temperatures, it is estimated that the electromagnet would engage at a temperature ranging from 250°F to 550°F, and the electromagnet would disengage at a temperature ranging from 100°F to 300°F, which were similar to the temperatures observed during the experimental tests.

5.4 Thermoelectric Power

Figure 32 illustrates how the voltage and power varied as a function of load, which is given in terms of current. The test was performed with the heater operating at its maximum energy-input rate. The hot side temperature was approximately 460°F and the cold side temperature was approximately 205°F, which resulted in a temperature difference of 255°F. The voltage data follows a linear line, with a decreasing slope, while the power data follows a parabolic curve. The open circuit voltage, which occurred at 0 amps, was approximately 4.85 volts. The peak power occurred at approximately half of the open circuit voltage. Using the equation for the best-fit curve of the power data, the peak power was calculated as 850 mW and occurred at a current of 370 mA. Using the equation for the best-fit curve of the voltage data at a current of 370 mA, the voltage at peak power was 2.37 V.

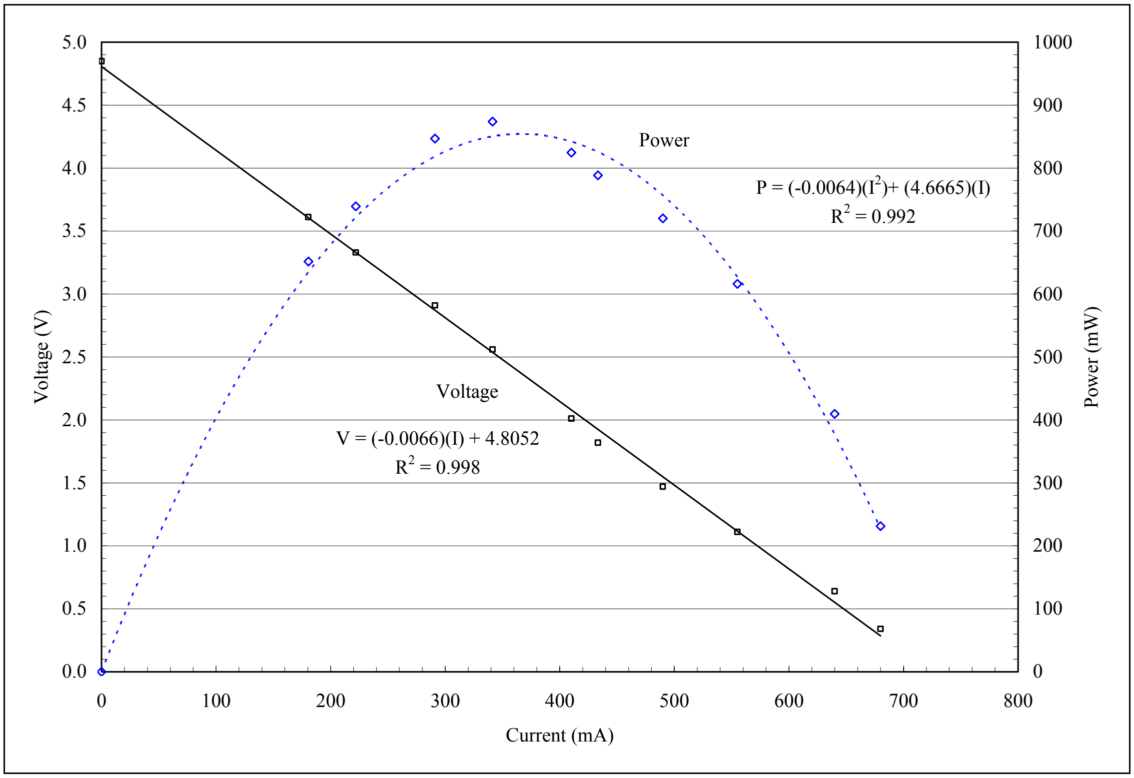


Figure 32. Voltage and power generated by a thermoelectric module as a function of the load, given in terms of current. The temperature difference across the module was approximately 255°F.

Table 4 illustrates how the power generated was a function of temperature. The data was obtained by operating the heater at its maximum energy-input rate in different ambient temperatures. No load was attached to the module during these tests. When the heater was operated outdoors at a temperature of 26°F, the steady state voltage was 5.60 V. When the heater was operated indoors at a temperature of 72°F, the steady state voltage decreased to 4.30 V. In addition, the temperature difference between the module's hot side and cold side increased from 260°F to 306°F. The better heat transfer can be attributed to the lower ambient temperature. During the outdoor test, there was also a slight breeze, less than 5 mph, which also may have contributed to the better heat transfer.

Table 4. Temperature effects on the power generated by the thermoelectric module

Ambient Temperature (°F)	Hot Side Temperature (°F)	Cold Side Temperature (°F)	$\Delta T = T_{hot} - T_{cold}$ (°F)	No Load Voltage (V)
72	480	220	260	4.30
26	458	152	306	5.60

5.5 CO Alarm Based Shutoff System

Tests were conducted with the test sample CO alarms to determine if tapping into the electrical circuit of the CO alarm affected its response to CO. Table 5 provides a summary of the alarm test results, which shows that both CO alarms met the response time requirements in UL 2034. When the red LED flashed, the voltages measured prior to the red LED peaked from 4.29 VDC to 5.86 VDC. Although not shown in Table 5, the CO concentrations displayed on the CO alarms were greater than the CO measured with the infrared gas analyzers by approximately 12 percent.

Table 5. Results of the CO alarm response tests

CO Concentration (ppm)	UL 2034 Allowable Response Time (minutes)	Time to Alarm (minutes)		Peak Voltage (volts DC)	
		#1	#2	#1	#2
70	60 - 240	80	86	5.86	4.68
100	NA[1]	46	50	4.41	4.29
150	10 - 50	32	35	4.43	4.29
400	4 - 15	8	7	4.35	4.84

1. UL 2034 does not require a test at 100 ppm.

The CO alarm was connected to a thermoelectric generator to verify that the thermoelectric generator could power the CO alarm. Figure 33 illustrates the voltage generated by the thermoelectric generator as a function of time, when the heater was operated at its maximum energy-input rate and its minimum energy-input rate, in a room with a normal oxygen concentration. When the heater was operated at its maximum energy-input rate, the voltage peaked at 5.3 volts in 6 minutes, and the voltage decreased to a steady state value of 4.3 volts in 28 minutes. When the heater was operated at its minimum energy-input rate, the voltage peaked at 4.9 volts in 5 minutes, and the voltage decreased to a steady state value of 4.1 volts in 23 minutes.

As the voltage increased from zero, the CO alarm went through a series of events. At 1 volt, a steady, low level, high pitch noise was emitted from the horn. Between 1 and 2 volts, the sound level of the high pitch noise increased. At 2 volts, the high pitch noise stopped, and the CO alarm went into its normal power-up routine, which lasted for approximately 30 seconds. After the power-up routine, the CO alarm went into a low battery mode, which occurs when the voltage is less than 3.3 volts. In the low battery mode, the letters "LB" appear on the digital display, the red LED flashes, and the alarm "chirps" every 30 seconds. The low battery mode continued until the voltage increased above 3.3 volts. Above 3.3 volts, the CO alarm went into its normal operating mode. Based on the experimental data, the thermoelectric module generated 3.3 volts in approximately 2.25 minutes when the heater was operated at its maximum energy-input rate, and 2.50 minutes when the heater was operated at its minimum energy-input rate.

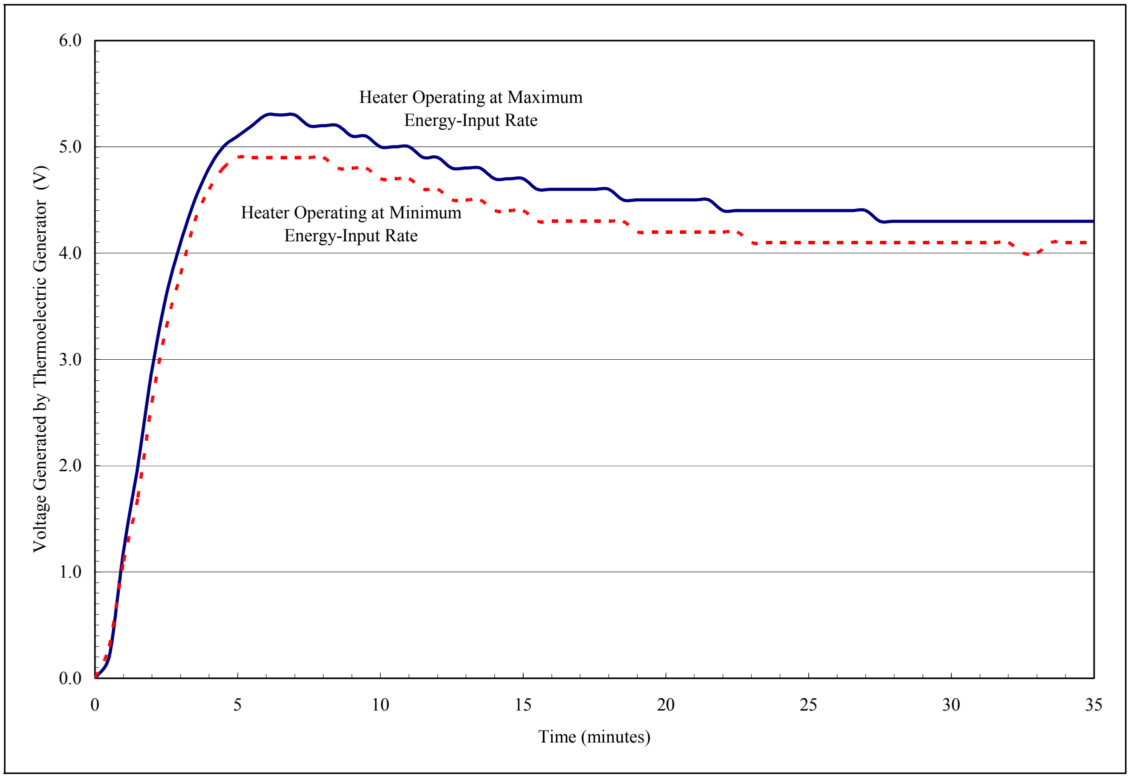


Figure 33. Voltage generated by the thermoelectric generator as a function of time and the energy-input rate of the heater, when a CO alarm was attached to the output of the thermoelectric generator and the heater was operated in a room with a normal oxygen concentration

Actual shutoff tests were performed with the CO shutoff system connected to a tank-top heater that was equipped with a thermoelectric generator. Figure 34 illustrates the concentrations of CO, CO_2, O_2, and HC, as a function of time, when the heater was operated at its maximum energy-input rate. In addition to the gas concentrations, the voltage produced by the thermoelectric module is plotted as a function of time. The CO shutoff system activated at 38 minutes after the heater was turned on. When the heater shutoff, the CO concentration was 283 ppm, the O_2 concentration was 13.9 percent, and the voltage generated by the thermoelectric module was 4.5 volts. The CO alarm activates based on a time weighted CO concentration measurement, which is calculated using an algorithm built into the CO alarm. The shutoff test was repeated several times, and each time the CO shutoff system functioned successfully and alarmed within the time limits prescribed by UL-2034.

The tests were then repeated with the heater set to its minimum energy-input rate. During these tests, the thermoelectric generator did not produce the electricity quickly enough, and the CO alarm went into a low battery mode. During this mode, the alarm chirps every 30 seconds and the red LED flashes. Because the red LED flashed, the shutoff circuit was activated and the heater shut off, even though there was no CO present. The CO alarm includes this low battery warning in order to notify the user that the batteries must be replaced. Attempts were made to increase the rate at which heat was transferred to the thermoelectric module, but with little success. Therefore, no shutoff tests could be conducted when the CO alarm was powered by the thermoelectric module and the heater was operated at its minimum energy-input rate.

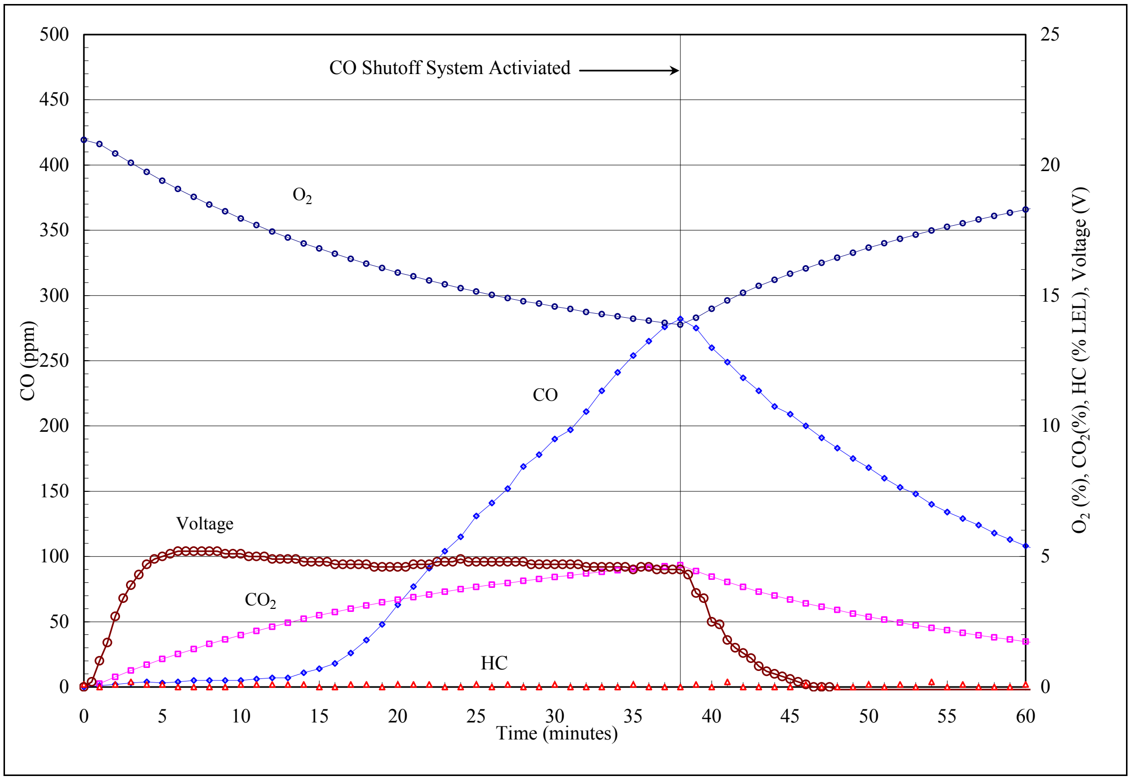


Figure 34. The concentrations of CO, CO$_2$, O$_2$, and HC, as a function of time, when the heater was operated at its maximum energy-input rate. In addition to the gas concentrations, the voltage produced by the thermoelectric module is plotted as a function of time.

6. DISCUSSION

6.1 Oxygen Depletion Effects

Carbon monoxide is a by-product of the combustion of a hydrocarbon fuel. The rate at which a tank-top heater generates CO is a function of many variables, including the amount of O_2 available for combustion. As the O_2 concentration decreases, the rate at which a tank-top heater generates CO increases. When the heater is operated outdoors or in well-ventilated areas, the oxygen will not be depleted in the surrounding atmosphere; therefore, the heater typically produces only trace amounts of CO. However, operating the heater in an enclosed area that is poorly ventilated, such as a tent or trailer, will result in oxygen depletion, which will cause the heater to generate CO more rapidly.

Staff tested three identical tank-top heaters in an oxygen-depleted environment. The heaters began to generate CO more rapidly when the O_2 concentration was depleted below approximately 16 percent. The heaters continued to operate until the O_2 concentration was approximately 13 percent, below which the flame self-extinguished. At an O_2 concentration of approximately 13 percent, the maximum steady state CO concentration in the 100 ft^3 test chamber ranged from 800 to 1358 ppm[11], depending on the test sample and the energy-input rate of the heater.

As the O_2 concentration decreased, several characteristics of the flame were affected. In particular, the burning velocity of the flame decreased, causing the flame to burn farther from the burner, and the length of the flame increased as the O_2 concentration decreases. By visually observing the flame, no change was apparent until the oxygen was depleted below approximately 16 percent. However, when the temperature was measured at various places on the heater, temperatures started to decrease when the O_2 concentration was depleted below approximately 18 percent.

6.2 CO Shutoff Systems

Staff explored several different shutoff systems to prevent tank-top heaters from generating hazardous levels of CO when operating the heaters in a poorly ventilated enclosed area. The shutoff systems fall into two general categories: those that activate based on the CO concentration, and those that activate based on the O_2 concentration. Oxygen is used as a proxy for CO, because the rate of CO generated by a heater is generally a function of the O_2 concentration. Of the five shutoff systems considered, all but one of the shutoff systems activate based on the O_2 concentration.

6.2.1 CO Alarm Based Shutoff System

Staff designed a CO shutoff system that combined a residential CO alarm with the heater's flame failure shutoff system. Staff selected a CO alarm equipped with an electrochemical sensor for the prototype systems, because the CO alarm required only 4.5 volts to operate, which was low enough to be powered by a single thermoelectric generator. The shutoff circuit consisted of a relay placed in series with the heater's rod-and-tube type thermocouple and the electromagnetic gas valve. When the CO detector alarmed, the relay opened, interrupting the flow of current to the electromagnet in the gas valve, causing the gas valve to close. Staff powered the relay by tapping into the CO alarm's alarming circuit, which did not appear to affect the function of the CO alarm. An algorithm built-into the CO alarm calculates the time-weighted CO concentration and determines when to activate the CO alarm.

When the heater was operated in an oxygen-depleted environment, the CO shutoff system worked as designed. The CO alarm activated when the algorithm built into the CO alarm determined that the

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[11] Although the tests were conducted in a relatively small room, the CO concentration in a larger room can be estimated from the experimental data. For example, when Heater A was operated at its maximum energy-input rate in the 100 ft^3 test chamber at an air exchange rate of approximately 3 ACH, the steady state CO concentration in the chamber was 972 ppm. The same CO concentration would be obtained in a 500 ft^3 room, if the air exchange rate was 0.6 ACH, assuming that the temperature and pressure inside the rooms were equivalent.

time-weighted CO concentration represented a hazard. The detector alarmed after operating the heater in the test chamber for 38 minutes, at which time the CO concentration reached 282 ppm. Using the CO concentration versus time data, the carboxyhemoglobin (COHb) level (i.e., the amount of CO that has been absorbed into the blood stream) was calculated[12] to be approximately 3.2 percent for a person at rest (Respiratory Minute Volume (RMV) = 6 L/min). For a moderately active person (RMV = 20 L/min), the COHb is calculated to be 7.9 percent. Therefore, no perceptible health effects would be expected in a healthy adult, since the COHb level is below 10 percent, which is the minimum level before the perceptible effects of CO poisoning are observed in a healthy adult.

To power the CO alarm based shutoff system, staff used a thermoelectric generator, which converts heat into electricity. With the thermoelectric generator attached to the tank-top heater, staff was able to generate sufficient power to operate the CO alarm and relays. The main problem with using the thermoelectric generator was the time lag associated with heating the thermoelectric module. For example, the relay in the shutoff circuit that allowed current to flow from the thermocouple to the electromagnetic gas valve required a minimum of 3.5 volts to close. Based on the design of the thermoelectric assembly (e.g., mounting bracket, heat sink, etc.), it took approximately 2.5 minutes for the module to generate 3.5 volts, during which time the user would have to depress the manual override button on the electromagnetic gas valve to allow gas to flow to the burner. To resolve this startup issue, a mechanical timer relay was installed. Although the mechanical timer relay resolved the startup issue when the heater was operated at its maximum energy-input rate, it did not resolve the problem when the heater was operated at its minimum energy-input rate. During these tests, the thermoelectric generator did not produce the electricity quickly enough, and the CO alarm went into a low battery mode, which caused the CO detector to alarm. Because the CO shutoff system activates anytime the CO detector alarms, the heater shut off even though there was no CO present. Attempts were made to increase the rate at which heat was transferred to the thermoelectric module when the heater was operated at its minimum energy-input rate, but with little success.

Additional work is required to prove that a CO alarm based system could be used reliably as part of a CO shutoff system. In particular, the following sensor issues must be addressed: reliability, ruggedness, repeatability, usable temperature range, and sensor life. In addition, the CO alarm would have to be modified so that it could power an electrical switch, such as a relay or a field effect transistor, when the CO detector alarms. Furthermore, a power source would have to be provided for the system, since the chemical sensor and the electrical switches require power to operate. Although the concept of using a thermoelectric generator to power the CO alarm has been demonstrated, it may be more practical to use batteries. Batteries do not have the thermal lag issue associated with them during the startup of the heater as do the thermoelectric generators, and some CO alarms can function on three AA batteries (4.5 V) for at least 1 year before the batteries must be replaced. Using batteries on portable gas-fired products is not unique, as some camp heaters have blowers that are powered with batteries.

6.2.2 <u>Oxygen Depletion System (ODS)</u>

The ODS system is a shutoff system which activates based on a change in the O_2 concentration. The ODS consists of a pilot burner and a thermocouple, which is connected to an electromagnetic gas valve. The flame on the pilot burner is very sensitive to slight changes in the O_2 concentration and will self-extinguish when the O_2 concentration falls below 18 percent. Such systems have been used successfully on unvented room heaters since the 1980's, and more recently on several camp heaters.

Two major issues must be resolved before a tank-top heater can be equipped with an ODS. The first issue relates to the gas pressure at which the heater and the ODS operate. Currently, tank-top heaters operate at a gas pressure of approximately 12 psig (gauge pressure), while the ODS operates at a gas pressure of approximately 0.4 psig. Because the energy-input rate of the radiant burner is a function of the gas pressure and the diameter of the gas orifice, decreasing the gas pressure would require the use of a larger diameter orifice to maintain an equivalent energy-input rate. However, a larger diameter orifice

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[12] Personal communication from Dr. Sandy Inkster, Directorate for Health Sciences, Division of Health Sciences

combined with a lower gas pressure would result in the gas exiting the orifice at a lower velocity. Because the momentum of the gas jet entrains the primary air used for the combustion process, gas flowing at a lower velocity would entrain less air. Therefore, sufficient air may not be entrained for the burner to operate properly, if the current burner is used at a decreased gas pressure. Therefore, integrating an ODS onto a tank-top heater will require a major redesign of the existing burner, if not an entirely new burner design.

The second issue that must be addressed is shielding the pilot flame from the wind. The pilot flame of the ODS is very sensitive to the wind and will extinguish at wind velocities greater than approximately 2 mph, based on discussions with industry personnel familiar with the operation of the ODS. Heaters designed for outdoor use must be able to operate in wind speeds up to 10 mph. It may be possible to shield the pilot flame from the wind, but shielding the pilot flame has a negative affect on the performance of the ODS. Increasing the shielding around the pilot flame reduces the flames sensitivity to changes in the O_2 concentration, resulting in a lower concentration (i.e., less than 18 percent O_2) required to self-extinguish the flame. Tests would be required to determine what affect the shielding would have on the performance of the pilot flame. If the wind issue cannot be resolved, it may be necessary to consider the use of an O_2 sensor in place of the ODS.

6.2.3 Thermocouple Placed Behind Burner Head Screen

U.S. Patent 5,941,699 describes a shutoff system, which activates based on a change in the O_2 concentration. The shutoff system consists of a thermocouple placed behind the burner head screen and an electromagnetic gas valve that has been modified to include a proximity sensor. As the O_2 concentration decreases, the flame will degrade over certain portions of the screen, which is sensed by the thermocouple as a decrease in temperature. Following this decrease in temperature, there is an increase in the temperature, which coincides with an increase in the CO concentration. Therefore, a correlation between temperature and CO can be obtained, which is unique to a particular burner design. When the temperature sensed by the thermocouple decreases, the current generated by the thermocouple decreases, resulting in a decrease in the magnetic field generated by the coil in the gas valve. A proximity sensor, such as a Hall-effect sensor, is used to detect the decrease in the magnetic field generated by the coil. Once a decrease in the magnetic field is detected, the proximity sensor acts as a switch and interrupts the flow of current between the thermocouple and the electromagnetic gas valve. The gas valve then closes, shutting off the gas to the burner.

Staff is not aware of any heater using the shutoff system described in Patent 5,941,699, and therefore, was not able to conduct any tests on such a system. In theory, the CO shutoff system described in Patent 5,941,699 should work. However, the patent does not provide details of the key components of the shutoff system, which are the proximity sensor and its associated circuitry. A solid-state device such as a Hall-effect sensor requires electrical power to operate. The voltage typically required for such a sensor is at least 2.5 volts. The only electrical power source currently on a tank-top heater is a thermocouple, which provides power to the electromagnetic gas valve. Because the thermocouple generates voltages in the millivolt range, a separate power supply, such as a battery, would be required to operate the Hall-effect sensor. Furthermore, if the Hall-effect sensor were connected in series with the solenoid gas valve, the input impedance of the sensor may prevent the solenoid valve from operating properly.

Another potential issue with this shutoff system is related to the proximity sensor, which activates based on a decrease in the voltage/current generated by the thermocouple. If a standard rod-and-tube type thermocouple is used, then the voltage will decrease during the initial heating of the thermocouple, because of the relative close proximity of the thermocouple’s cold junction to the hot junction. Therefore, the shutoff system may activate unintentionally during the startup of the heater.

6.2.4 Thermocouple Placed in Other Locations

The shutoff system described in Patent 5,941,699 uses a thermocouple placed in the plenum area behind the burner head screen to detect small changes in the screen temperatures. Staff thought that it might be possible to place a thermocouple in a different location, which could detect when the flame began to lift off the burner or when the length of the flame began to increase.

Based on the temperature data from the heater temperature tests, the temperatures on the outside of the heater's plenum (locations 2, 3, 4 and 7) all decreased as the O_2 concentration decreased below approximately 19 percent. This decrease in temperatures, due to a change in the flame characteristics, occurred much earlier than was visually observed. Visually, the flame did not change in appearance until the O_2 concentration decreased below approximately 16 percent. Although the surface temperatures on the plenum provided an early indication of a change in the O_2 concentration, the change in the temperatures was not significant enough to decrease below the point at which the thermoelectric gas valve would close, which was estimated to be as low as 250ºF. Therefore, a CO shutoff system that relies on a decrease in a temperature to deactivate the electromagnet in the gas valve does not appear feasible.

Although not investigated by staff, it may be possible to use a microprocessor-based system to detect a decrease in the temperature sensed by the thermocouple located on the outside of the heater's plenum. In such a system, the microprocessor may be able to calculate a time weighted average of the signal from the thermocouple (e.g., voltage or current) to verify that the temperature is actually decreasing with time and that the decrease is not due to normal temperature fluctuations. Once the temperature has been determined to be consistently decreasing, the shutoff system would be activated. Such a system would require electrical power to operate.

Another possible application for a microprocessor is to measure the difference between two thermocouples and determine when there is a change in this difference. For example, when the heater was operated in a room with a normal oxygen concentration, the temperature sensed above the burner (#6) and in front of the burner (#1) were approximately equal, after the heater had been operating for more than 1.5 minutes (see Figures 23 and 24, page 34). Therefore, after the initial start-up of the heater, the temperature difference between location #6 and #1 remained approximately constant over time. However, when the heater was operated in a room with a depleted oxygen concentration, the temperature difference between locations #6 and #1 did not remain constant, but increased at a certain O_2 concentration, as shown in Figure 35. When the heater was operated at its maximum energy-input rate, the temperature difference remained fairly constant (~ 0°F) until an O_2 concentration of approximately 17.5 percent. Below 17.5 percent O_2, the temperature difference between locations #6 and #1 increased at an approximate steady rate. At an O_2 concentration of 14 percent, the temperature difference had increased to approximately 600°F. When the heater was operated at its minimum energy-input rate, the temperature difference remained fairly constant (~ 50°F) until an O_2 concentration of approximately 16 percent. Below 16 percent O_2, the temperature difference between locations #6 and #1 increased at an approximate rate of 150°F per 1 percent decrease in the O_2 concentration. At an O_2 concentration of 14 percent, the temperature difference had increased to approximately 400°F.

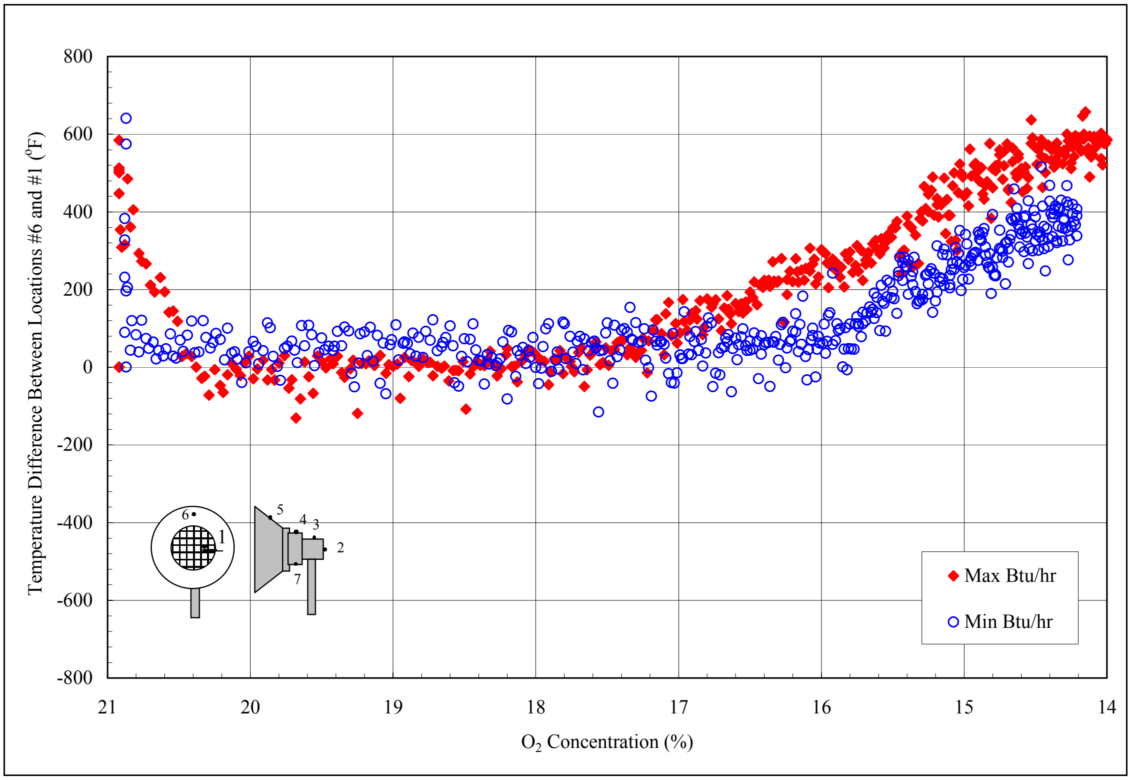

Figure 35. Temperature difference between the temperature sensed above the heater (#6) and the temperature sensed in front of the heater (#1), when operating the heater in an oxygen-depleted environment

6.2.5 Bimetallic Switch

As oxygen depletion occurred, the flame length was observed to increase. Therefore, staff thought that it might be possible to use a bimetallic switch to detect when the flame started to elongate. The ideal place to locate the switch appears to be somewhere at the top of the burner, since the hot gases from the flame are less dense than the surrounding air, causing the hot gases to flow upwards. A sensor could be mounted on the backside of the heat reflector, so that the sensor would detect the surface temperature. A sensor could also be mounted off the surface of the heat reflector, in the front, so that the sensor would detect the air temperature. During the heater temperature tests, the temperature at both of these locations was at least 800ºF. Therefore, a bimetallic switch designed for high temperature applications would be required.

The main issue with using a bimetallic switch has to do with the set point temperature at which the switch will activate. Because the heater can operate at different energy-input rates, the temperature sensed by the bimetallic switch will vary. For example, the steady state temperature on the backside of the heat reflector (location 5 in the temperature tests), ranged from 800ºF to 860ºF, when the heater was operated at its minimum and maximum energy-input rates, respectively. When the heater was operated at its minimum energy-input rate during the oxygen depletion tests, the temperature peaked at approximately 880ºF, at an O_2 concentration of approximately 15.4 percent. The peak temperature of 880ºF is very close to the normal operating temperature of the heater operating at its maximum energy-input rate. Slight temperature fluctuations during normal operating conditions could cause the shutoff system to activate unintentionally during normal operation. Additional tests are required to determine what effect the ambient temperature has on the temperature sensed by the bimetallic switch. Furthermore, tests with identical heaters are required to confirm that all the heaters will perform similarly (i.e., the temperature sensed by the bimetallic switch will be similar).

7. CONCLUSIONS

Based on some preliminary tests, CPSC staff believes that an automatic CO shutoff system is technically feasible for tank-top heaters. The shutoff systems considered in this report fall into two general categories: those that activate based on the CO concentration and those that activate based on the O_2 concentration. A shutoff system based on the O_2 concentration was considered, because the rate of CO generated by a tank-top heater is, in general, a function of the O_2 concentration. This report is not intended to cover all possible shutoff technologies, only ones CPSC staff believes are most likely to be suited for portable heater applications.

Several of the shutoff systems require the use of an external power source, such as batteries, to operate. Staff was able to demonstrate that a thermoelectric generator could be used to convert heat into electrical power, in order to power a shutoff system. However, because there are issues with the time required to heat the thermoelectric module during the start-up of the heater, a battery-based power source appears more practical for a portable heater application.

This report is intended as a first step in the development of a potential CO shutoff system for tank-top heaters. Additional testing and development work would be necessary to explore the practicality of various designs of CO shutoff systems.

8. ACKNOWLEDGEMENTS

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John Worthington, Directorate for Laboratory Sciences, Division of Mechanical Engineering, provided technical expertise related to mechanical design and fabrication issues.

Susan Vagts, Directorate for Epidemiology, Division of Hazard Analysis, provided the hazard sketch of portable type propane heaters.

Dr. Sandy Inkster, Directorate for Health Sciences, Division of Health Sciences, provided carboxyhemoglobin analysis of the carbon monoxide data.

Robert Franklin, Directorate for Economic Analysis, provided information on the tank-top heater market.

Norvan Allen, Bridgette Cottral, Bini Dahlman, Jay Hammond, Henry Glogowski, Susan Guenette, Noel Jones, Laurie Lovelace, Jacqueline Martinez, Randall Poth, Julie Poyer, William Robison, Robin Ross, Cecil Smith, Pete Viola, and Zannie Weaver, Directorate for Field Operations, conducted the field surveillance of tank-top heater use.

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APPENDIX A. SUMMARY OF OXYGEN DEPLETION TEST DATA

Heater Sample	Test #	ACH (1/hr)	Energy-Input Rate (Btu/hr)	CO Maximum (ppm)	O_2 Minimum (%)	CO_2 Maximum (%)	HC (% LEL)	Length of Test (hrs)	Reason Heater Shut Off [1]	Average CO Generation Rate (ft^3/hr)
A	1	3.30	12,800	253	13.5	4.7	0	1.5	SS	0.056
	2	2.56	10,100	375	13.5	4.7	0	1.7	SS	0.067
	3	2.98	13,100	972	12.9	5.2	2	2.00	SS	0.178
	4	2.50	10,600	989	12.9	5.1	1	2.75	SS	0.168
B	1	2.93	12,900	800	13.0	5.1	1	2.00	SS	0.139
	2	2.58	10,000	449	13.2	4.9	0	1.67	SS	0.085
	3	2.39	9,200	443	13.8	4.5	0	1.83	SS	0.076
	4	2.54	9,500	465	13.6	4.7	0	1.75	SS	0.085
	5	2.31	9,900	1350	12.8	5.2	4	3.00	SS	0.195
C	1	2.52	12,400	1070	13.1	5.2	5	1.83	SS	0.177
	2	1.39	9,650	627	12.7	5.4	2	0.83	FSE	0.097
	3	1.91	9,840	709	12.9	5.3	3	1.58	FSE	0.095
	4	2.09	9,480	513	13.6	4.7	0	1.75	FSE	0.088
	5	2.00	9,510	484	13.4	4.9	0	1.75	FSE	0.081
	6	1.90	9,480	868	12.9	5.3	4	1.42	FSE	0.120
	7	2.02	9,210	591	13.1	5.1	0	2.00	SS	0.097
	8	1.89	9,390	1358	12.9	5.3	4	2.75	SS	0.180

1. SS = Concentrations of CO, O_2, CO_2, and HC all reached steady state; FSE = Flame Self-Extinguished,