UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
WASHINGTON, DC 20207

Memorandum

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___ Excisions/Revisions
X Firm has not requested further notice
10-11-02

TO	:	The Commission Todd A. Stevenson, Secretary
THROUGH	:	Melissa Hampshire, Acting General Counsel for Thomas W. Murr, Jr., Acting Executive Director
FROM	:	Jacqueline Elder, Acting Assistant Executive Director Office of Hazard Identification and Reduction Andrew M. Trotta, Electrical Engineer Directorate for Engineering Sciences
SUBJECT	:	Contractor Report on Evaluation of Sensor and Control Technologies to Address Cooking Fires on Glass Ceramic Cooktops

Attached is a contractor report on sensor and control technologies to address cooking fires on glass ceramic cooktops. This report was completed by Arthur D. Little, Inc. (ADL) in support of efforts by the U.S. Consumer Product Safety Commission (CPSC) staff to address cooking fires.[1] Each year cooking fires from food igniting inside a cooking utensil cause an estimated 47,200 residential structure fires, claiming 80 lives, injuring 2,440 victims, and resulting in $134.6 million in property loss[2].

Glass ceramic cooktops, as shown in the photo, are primarily electric-powered ranges that feature a sheet of specially-formulated ceramic glass with radiant heating elements located beneath the glass surface. These cooktops offer an attractive appearance as well as ease of cleaning. Advances in the manufacturing of ceramic have improved cooking performance so that cooking times are nearly equivalent to those of a standard

[1] Funds for this study were provided by the U.S. Fire Administration.
[2] Smith, Linda E. and Greene, Michael A.; CPSC staff memorandum, *Updated Estimates of Rangetop Cooking Fires*; March 9, 2001.

NOTE: This document has not been reviewed or accepted by the C coil-type electric range. Glass ceramic cooktops are a growing segment of range sales; the percentage of total range sales that included glass ceramic grew from about 12% in 1996 to about 22% in 2000.[3]

In 1998 and 2000, CPSC staff successfully demonstrated pan temperature-sensing concepts to prevent cooking fires on gas and coil-type electric ranges using a pan contact sensor. This type of sensor is not suitable for a glass cooktop. CPSC staff initiated the ADL study in 2002 to determine whether there are technologies in existence or on the horizon that may allow the accurate measurement of pan temperatures on glass ceramic cooktops.

The ADL study identified various sensor and control technologies that may be applicable for use on glass ceramic cooktops. The concepts that show the most promise are:

- Optical infrared systems that look through the ceramic glass or through a "window" inserted into the glass to measure pan temperature without making contact with the pan or glass.
- *Combinations of sensors that are able to infer pan temperature by measuring the* temperature on the bottom surface of the glass.

The results of ADL's research demonstrate that there are conceptual solutions to the challenge of measuring pan temperature on glass ceramic cooktops. CPSC staff plans to share this report with the industry in continuing attempts to encourage industrial research and development that will lead to the introduction of new safety features in all types of cooking ranges. The report will also be provided to Underwriters Laboratories, Inc. as CPSC staff continues to promote the adoption of performance requirements in the voluntary standards for electric ranges to help prevent cooking fires. Using FY 2002 funds from the U.S. Fire Administration, CPSC staff plans to pursue additional research to evaluate and demonstrate the most promising candidate technologies for use with glass ceramic cooktops.

Attachment

[3] Carbone, P. C. and Benedek, K.; *Technical, Practical and Manufacturing Feasibility of Technologies to Address Surface Cooking Fires*; Arthur D. Little, Inc., 2001.

An Evaluation of Sensor and Control Technologies to Address Cooking Fires on Glass Ceramic Cooktops

Final Report

Report to:

United States Consumer Product Safety Commission

February 25, 2002

Order No. CPSC-S-01-1193

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390

Reference 75313

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1. Background

The Consumer Product Safety Commission (CPSC) has sponsored work during the last six years to develop technology to reduce the risk of surface cooking fires. In the early phases of this work, the CPSC used the resources of the National Institute of Standards and Technology to determine if there was a common, measurable, pre-ignition indicator for range top cooking fires. From this work, pan temperature was found to be the most consistent, measurable, pre-ignition indicator. Follow-on phases to this work led to the design and early development of a thermocouple-based control system to limit pot temperature to a level safely below pre-ignition conditions.

In May 2001, Arthur D. Little completed a review of the technical, practical, and manufacturing feasibility of this and other technologies to address surface cooking fires. This analysis concluded that a pot temperature sensor system that was designed to prevent food ignition in the pan had potential for mitigating cooking fires. However, there were reliability and durability issues that needed to be addressed before it could be implemented in open coil electric ranges and gas ranges. In addition, the pot sensor approach as developed thus far is not feasible for the glass ceramic (smoothtop) cooktop - a rapidly growing segment of the surface cooking market. Therefore, the CPSC requested that Arthur D. Little conduct a study on existing technologies to sense pan temperature through a glass ceramic cooktop.

2. Objective

The objective of this study is to review available sensor and control technologies that can help prevent ignition of cooking materials in a pan on a glass ceramic cooktop. The most promising technologies are characterized by method of operation, technology status, and application issues for use on glass ceramic cooktops.

3. Approach

The program consisted of two major tasks: the identification of potential sensor technologies to detect a pan over-temperature condition and the evaluation of these technologies with respect to their potential to reduce cooking fires and their development needs for application to cooking products.

3.1 Identification of Potential Sensor Technologies

The technology survey focused on sensors that could detect pan temperature through the glass ceramic. This survey included sensors that could directly measure temperature of the cooking pan and sensors that could infer pan temperature by measuring other physical properties that are dependent on pan or pan content temperature. As an example of other physical properties that can infer pan temperature, the acoustic signal from a cooking process, with other information such as the power level into the heating element, can be used to detect a boil-dry situation and turn the heating element off before elevated pan temperatures occur.

To guide our search, a brainstorming session was conducted with Arthur D. Little engineers and physicists with temperature measurement experience in a variety of industries. The brainstorming session was structured around the particular design constraints of the ceramic glass electric cooktop (e.g., the properties of the glass ceramic and of the various pots and pans used in cooking). The types of cooking processes that lead to fires (e.g., high temperature deep fat frying with oil) were also outlined. The brainstorming session identified potential sensor technologies and approaches to measuring pan temperature on a glass ceramic cooktop. As a further guide to the technical literature search, this session identified other industries that face comparable temperature measurement challenges.

The technology survey was performed on a variety of patent databases and technical literature databases as listed in Appendix B.

3.2 Evaluation of Potential Sensor Technologies

The sensor systems discovered in the technology survey were listed and categorized within technology groups to facilitate the evaluation process.

Each technology includes a brief description of how it measures or infers pan temperature, its potential to reduce cooking fires on glass ceramic cooktops, and an evaluation of development needs and issues. Embedded in the evaluation of development needs and issues is a technology's potential to be designed in such a way as to meet industry standards for reliability, durability, cooking performance, safety, operability and cost.

As an initial screen, only technologies that could be fully integrated into the glass ceramic cooktop assembly were considered. Technologies that require the user to perform additional tasks or use additional equipment were eliminated. The Simmer Sentry, developed by the Gas Research Institute, was one such technology that was eliminated because it requires the user to manually insert a temperature "wand" into the pot in order to monitor food content temperature. Technologies mounted elsewhere in the kitchen or in the ventilation hood were also not considered. Other proposed schemes that required the use of a specific pan or an additional appliance component were also eliminated. For example, it is feasible to create a "smart pan" with embedded temperature sensors and wireless systems that could communicate with the cooktop controller. One could also conceive of a "smart food" module or capsule that could be included with the food or in the cooking water or oil that would sense temperature and communicate with the controller using wireless technology.

These remote temperature measurement technologies have the advantage of directly sensing the food content or pan temperature. They could probably detect the pre-hazard conditions that lead to a fire. However, technologies separate from the cooktop itself may not achieve the market penetration or usage rate needed to provide significant societal benefit from the technology. Therefore, this study focused on safety approaches that could be embedded in the cooktop itself.

4. Sensor Technology Survey

The technology survey focused on sensors that could detect pan temperature through the glass ceramic. This survey included sensors that could directly measure temperature of the cooking pan and sensors that could infer pan temperature by measuring other physical properties that are dependent on pan or pan content temperature.

The glass ceramic cooktop system components are first defined in Figure 4.1. These components define the technology classes for measuring or inferring pan temperature that are shown in Figure 4.2.

The technology survey was performed on a variety of patent databases and technical literature databases as summarized in Appendix B. Industries covered include aerospace. materials manufacturing. automotive. agriculture. space. military, and energy systems research associated with government and private industry. It is important to note that the technology survey was not limited to cooktop applications or to terminology shown in Figure 4.2 – these are classification systems for the results of the survey. The survey used a variety of keywords associated with temperature sensing in remote applications. enclosed spaces. at interfaces. with radiant energy sources, on surfaces, and other instances that could potentially be related back to the glass ceramic cooktop.

4.1 The Glass Ceramic Cooktop System

The heating element. glass ceramic, and cooking utensil define the smoothtop cooking environment for a temperature sensor. Ultimately. the types of foods used and the cooking processes on the cooktop also need to be considered when developing a cooktop safety system that incorporates one or more sensor technologies.

The various heat transfer paths and temperatures relevant to the glass ceramic cooktop system are listed in Figure 4.1. The energy entering the heating element is primarily transferred to the cooking pan through conduction and radiation. The remainder of the energy is lost from the heating element wall or conducted radially through the glass ceramic. The amount of heat conducted radially through the glass is a very small amount because of the low conductivity of the glass ceramic.

The temperature and heat transfer paths shown in Figure 4.1 are used to structure the technology classes for potential solutions for determining pan or food temperature as shown in Figure 4.2. The solutions are broken up into direct means for detecting pot temperature and indirect means. It is also assumed that, for each technology class, appropriate derivatives with respect to time or area would be considered as required for the safety system. Items grayed out in Figure 4.2 are either unattractive options for reasons described earlier (e.g., contact measurement of pan that would require piercing the ceramic glass or a "smart pan" that tells the cooktop how hot it is via wireless communication) or are unlikely to provide a potential solution (e.g., changes in the amount of heat lost radially through the glass).

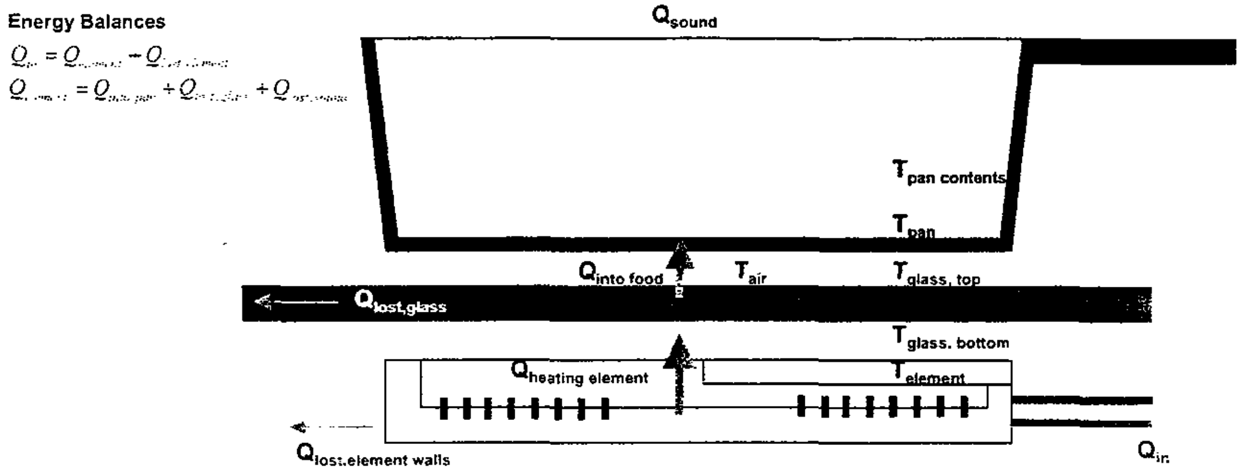


Figure 4.1: Glass Ceramic Cooktop System

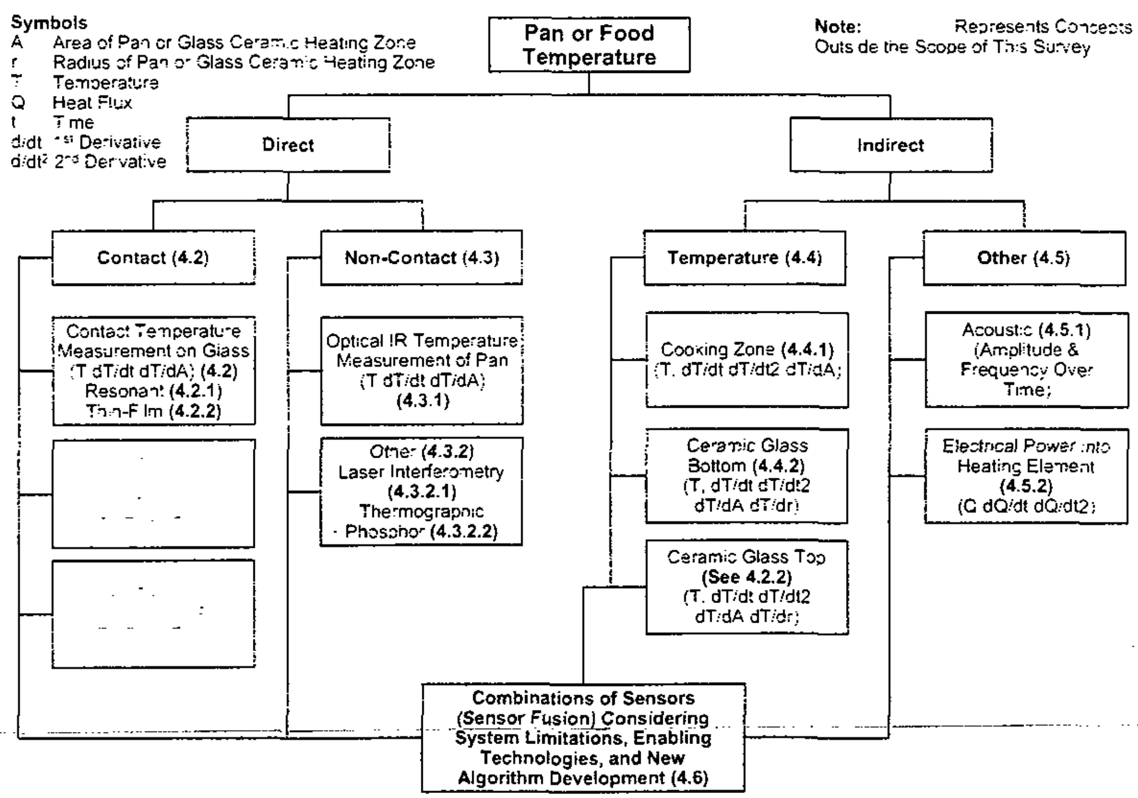


Figure 4.2: Technology Classification for Potential Solutions to Cooktop Temperature Measurement

One approach to preventing cooktop fires could be the sensor fusion or combination of multiple technologies as shown in the bottom box of Figure 4.2. An example of sensor fusion is using acoustic signatures and power level setting to determine a boil-dry condition, as outlined below in a General Electric patent. An example of an enabling technology is thermoelectric cooling, which can increase the sensitivity of an optical infrared detection system by maintaining the optical sensor at a lower temperature.

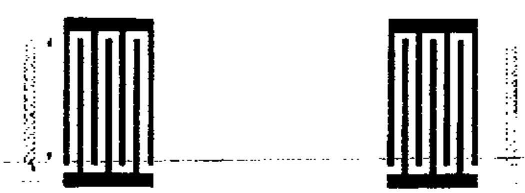
4.2 Direct, Contact Measurement

The industry perspective that motivated this study is that direct, contact temperature measurement through a hole in a glass ceramic cooktop is not feasible. Given that the attractiveness of the glass ceramic cooktop comes from its smooth surface and associated cleanability, it is clear that penetrations through the glass or protrusions above the glass may not be acceptable to manufacturers or consumers.

The literature search revealed continuing work on a variety of sensors that could directly measure pan temperature without penetrations through the glass or large protrusions above the glass. Resonant temperature sensors and thin film thermocouples are two technologies that can be mounted to the top of the cooktop ceramic glass and measure pan temperature by contacting the pan. The application of temperature sensors to the top of a glass ceramic cooktop was not found in our literature survey, but the potential benefits may warrant additional work in this area.

4.2.1 Resonant Temperature Sensors

Resonant temperature sensors use surface acoustic waves to detect changes in temperature. [Sachs et al., Drafts] Quartz is a commonly used material in these sensors. A properly chosen material, a properly cut material, and a properly oriented material can be very sensitive to temperature changes. Figure 4.3 shows a typical surface acoustic wave device. A radio frequency signal can be used to power the device, making it a wireless temperature sensing system. A radio frequency signal would be received by a miniaturized antenna on the input transducer side below. The temperature-dependent propagation of the surface acoustic wave would influence a radio frequency signal on the output transducer side through a phase shift that is a function of the temperature of the sensor.



Source: *Acoustic Wave Technology Sensors*, Microsensor Systems Inc.

Figure 4.3: General Structure of Surface Acoustic Wave Sensor

This technology is attractive because it is wireless and self-powered – the signal carries the information and the energy required to get an indication of temperature. An example of an existing, compact wireless system using surface acoustic waves is tire pressure monitors now on many automobiles. [Drafts] The wireless tire pressure sensor in automotive application weighs less than one gram. No applications of this technology as a "wireless" temperature sensor were found, but conference papers found in the literature search discussed this potential application. [Sachs et al.]

Surface acoustic wave sensors could conceivably be used on the surface of a smoothtop cooktop as a temperature sensor. Size, resistance to abrasion, and high temperature operation would need to be addressed for smoothtop cooktop application.

Temperature sensors on the surface of the smoothtop represent a new application. None of our literature searches revealed any efforts to determine if glass ceramic surface temperature measurements can accurately sense pan temperature and prevent cooktop fires. If good contact with the pot or pan is made, such a system could potentially indicate an over-temperature condition on the pot or pan.

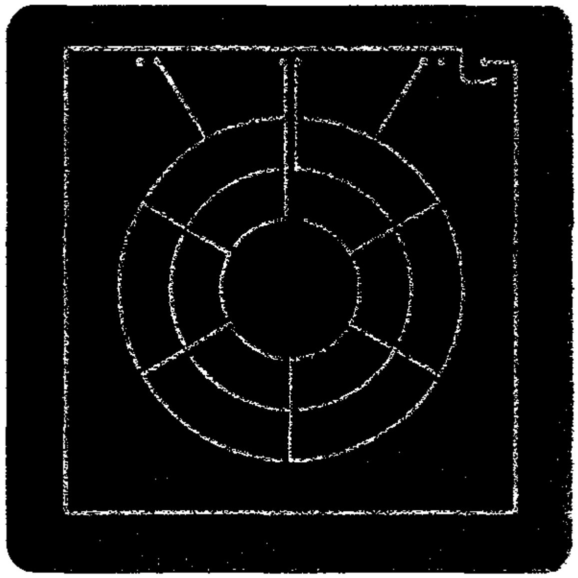
4.2.2 Thin-Film Thermocouples

Multiple patents in the literature describe various types of thin and thick film thermocouple temperature sensors. Thermocouples are composed of two dissimilar metals that generate a voltage when subjected to a temperature gradient. Thin film thermocouples do not have the wires associated with conventional thermocouples – the thin traces can be routed away from the cooking zone and attached to lead-wires in sheltered or hidden locations.

Thin films are typically one micron thick or less. Thick films are typically in the range of 5 to 25 microns thick. [Feldman] The type of process used determines the resulting thickness – more expensive chemical vapor deposition and other vacuum-based processes enable a very thin coating of one micron thickness or less. More conventional silk screening processes produce thicker coatings. One advantage of the very thin coatings is that they are highly transparent and therefore less visible to the user. Thin film thermocouples can be deposited on a variety of materials, including glass ceramic, mica, porcelain enamel, and stainless steel. [Thermo-Stone]

Thermo-Stone USA, LLC is one company that markets these thin films as heating elements. Thermo-Stone patents mention the application of these thin films to temperature sensing. [Feldman] Thermo-stone's current size limitation for the substrate is 16" x 30", which is smaller than the most common 36" x 21" smoothtop cooktops. However, thick films produced with silk screening processes will not have any size limitations since current smoothtop cooktops already go through a decorative silk screening step.

Aerospace applications are another area where thin-film thermocouples are heavily used. [NASA] Thin-film thermocouples are advantageous because of their low thermal mass and fast response time. The NASA and Thermo-Stone references above represent a few of the many references found to thin-film thermocouples in the literature search.



Source: Thermo-stone® USA, LLC. http://www.thermostone.com/images/tstone_hotplate_600.gif

Figure 4.4: Thin Film Heating Element Used on a Hot Plate

No existing application of thin film thermocouple technology to sensing cooktop temperature was found. As mentioned in the previous section, there is potential for thin film thermocouples to indicate the temperature of a pan where contact is made with the pan. It is conceivable that an array of thin film or thick film thermocouples could cover a portion of the heating element area or a large wedge so that the temperature of warped pans could still be sensed by at least one thermocouple in the array. Additional testing could determine the applicability of these technologies to monitoring pan bottom temperature.

4.3 Direct, Non-Contact Measurement

This class of technologies measures the infrared (IR) radiation emitted from the pan to measure temperature without requiring contact with the cooking utensil. Other non-contact temperature measurement systems are also described.

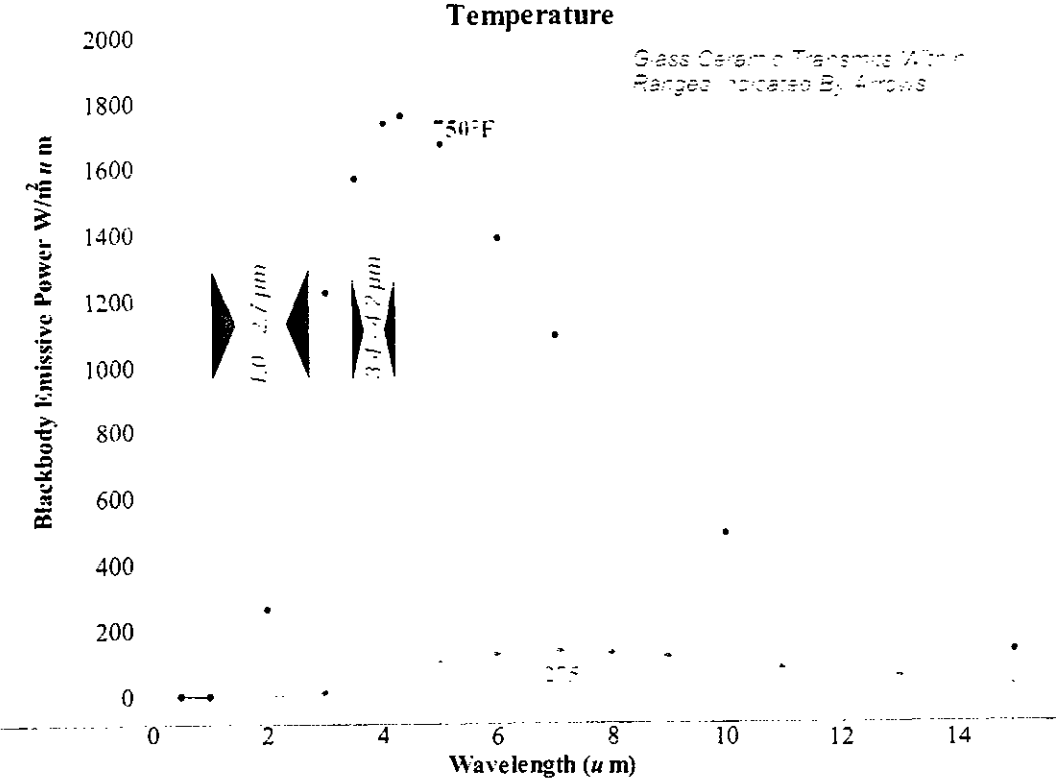
4.3.1 Optical IR

There are several possible ways to use IR to detect pan temperature. Infrared energy can be detected through the glass ceramic under certain conditions. A 'window' of quartz or other optical material with high transmissivity could conceivably be inserted into holes through the glass ceramic. Sensors that are located above the cooktop can view the side of the pan and measure temperature.

4.3.1.1 Technology Description

All objects emit infrared radiation as a function of their temperature. Infrared radiation is in the invisible portion of the electromagnetic spectrum at wavelengths longer than visible light (the near and mid infrared spectrum most useful for temperature measurement ranges from approximately 0.7 microns to 30 microns). The infrared radiation emitted at various wavelengths depends on the temperature of the body – the higher the temperature the shorter the wavelength where the peak amount of energy is released. Planck's Law describes the radiation emitted at given wavelengths for an object at a given temperature. Figure 4.5 shows the radiation emitted as a function of wavelength for various pan temperatures relevant to surface cooking. The wavelength where the peak amount of energy is emitted for a given temperature is described by Wien's displacement law. Figure 4.6 shows the wavelengths of peak intensity for temperatures relevant to surface cooking.

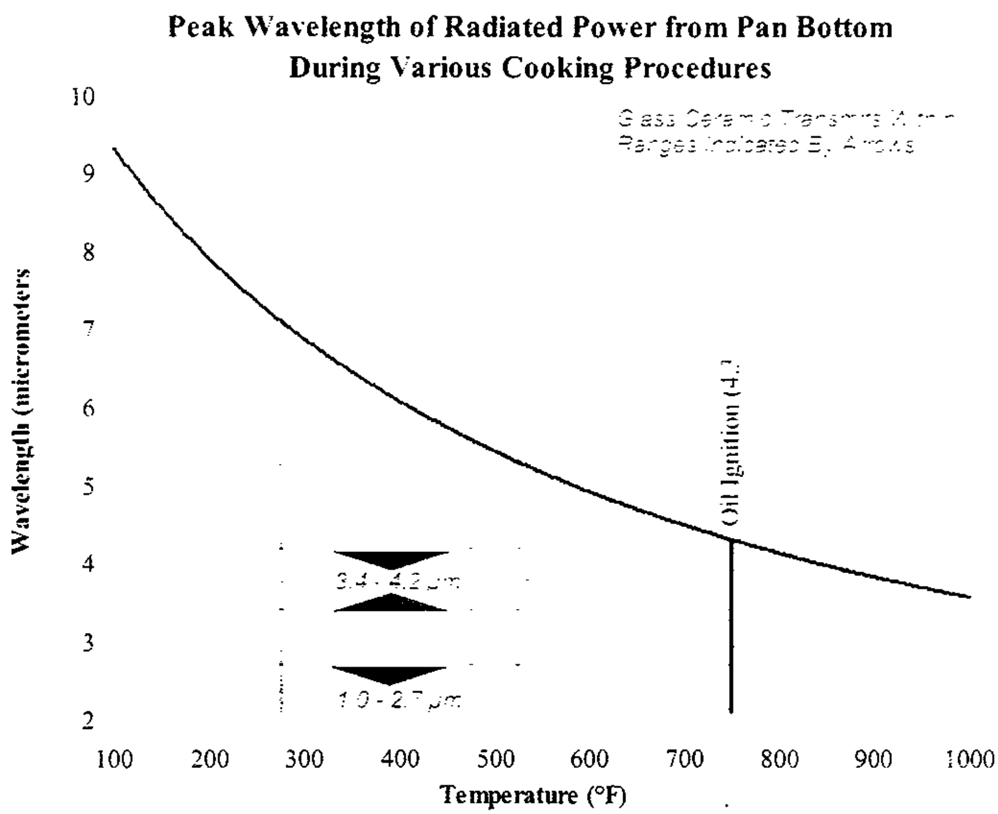
Blackbody Emissive Power As a Function of Wavelength and Temperature



Source: Arthur D. Little (Cooking Temperatures) and Schott Inc. (Glass Ceramic Transmission Properties)

Figure 4.5: Blackbody Emissive Power as a Function of Wavelength and Temperature for Pans at Water Boil Temperature (275°F), Searing (475°F), Frying (525°F) and Oil Ignition (750°F)

Figure 4.5 shows the maximum amount of energy that can be emitted by an object at four selected temperatures – also known as blackbody conditions. Most objects emit a fraction of this total energy. and the ratio of the energy emitted by a given object compared to a blackbody at the same temperature is the emissivity. Emissivity can vary by material. material finish. temperature, and by the angle with respect to the surface being measured. For surface cooking, many different materials and surface finishes are available on pots and pans. Stainless steel. aluminum. cast iron, copper, and ceramic pans are common. The emissivities of these pots and pans vary from less than 0.1 to greater than 0.9. Polished metals will typically have lower emissivities than oxidized surfaces. Any optical IR measurement system needs to be able to measure the temperature of the most common pots and pans, and that requires methods to compensate for the different emissivities of the different pans.



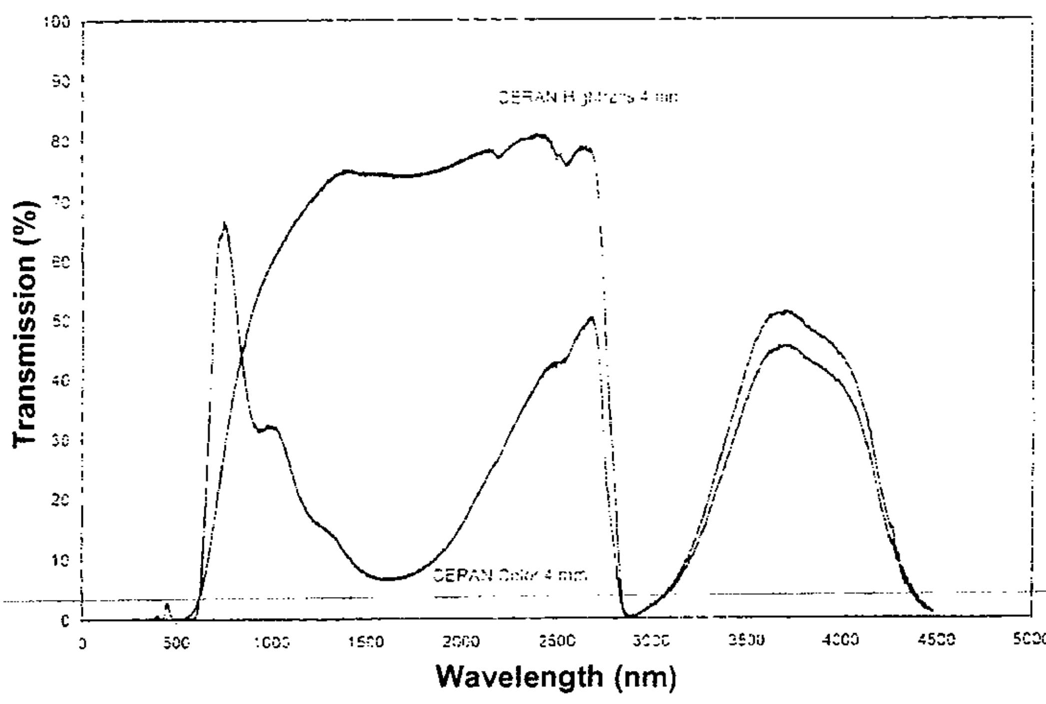
Source: Arthur D. Little

Figure 4.6: Peak Wavelengths for IR Measurement of Pan Temperature & Typical Transmission Bands for Glass Ceramic

Dual-wave IR measurement could be used to compensate for different cooking utensil emissivities. Dual wave IR measurement looks at the intensity of energy emitted at two wavelengths. By looking at the ratio of energy emitted at these two wavelengths. the temperature of a pan can be determined without knowing the emissivity as long as the emissivity of the pan is constant at both wavelengths. A graybody condition for a given material is defined as a constant emissivity over all wavelengths or for wavelengths used in a measurement system.

Dual wave IR measurement and other IR measurement systems are frequently mentioned in current literature for applications in a variety of industries from agriculture to high temperature metals processing. Dual and multiple wavelength IR measurement with micro-mechanical sensors (MEMS) are also under development. [Thundat et al.]

The actual sensor that receives the infrared radiation is either a photoelectric or a thermal detector. [Gruner] Photoelectric detectors output a current in response to incident photons. Common photoelectric sensors include Germanium, Silicon, Lead-silenide, Mercury-cadmium telluride, and Indium-gallium-arsenide. Indium-gallium-arsenide is increasing in use due to its low cost and increased sensitivity compared to Germanium. Thermal sensors create a voltage output as a function of temperature increase when exposed to incident radiation. Thermal sensors include bolometers (change in resistance with temperature) and thermopiles (voltage change as a function of temperature difference). The IR sensors can be quite compact and could be packaged in a manner that would allow them to be mounted in an electric cooktop. There are temperature compensation methods to allow these sensors to operate in the cooktop environment. Thermo-electric cooling could also be used to increase sensitivity. Cost reduction and size reduction are continuing trends with both photoelectric and thermal detectors.



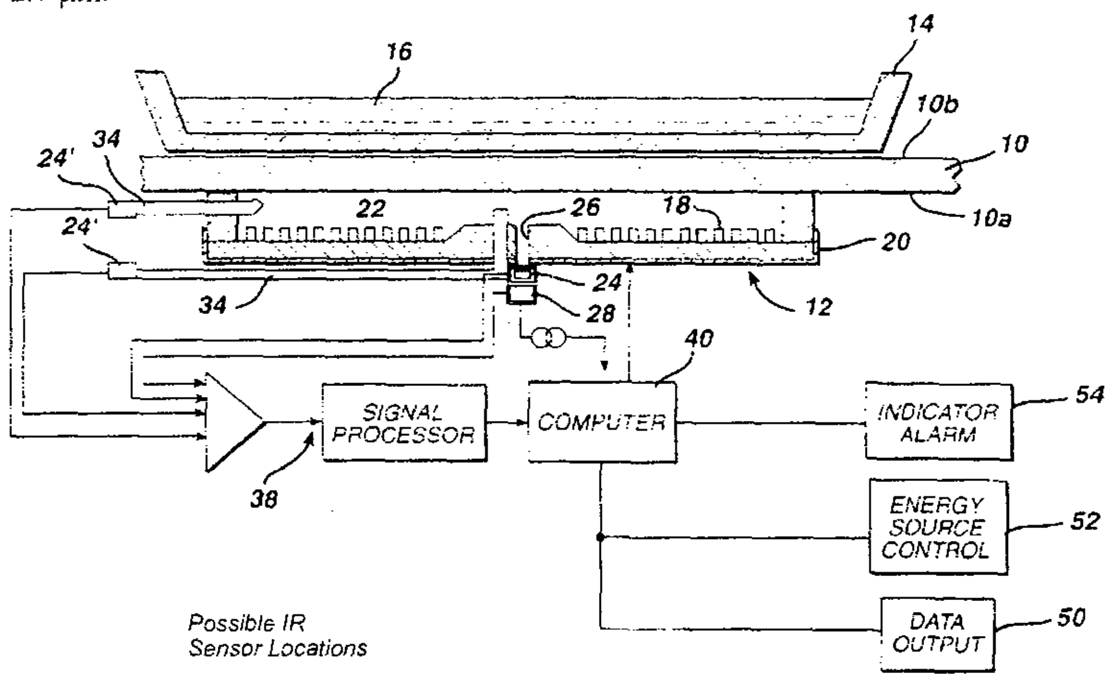
Source Schott Inc

Figure 4.7: Transmission Curve for a Common Glass Ceramic

The remaining components required for a non-contact IR measurement system are the optics required to gather and focus the infrared energy onto the detector and any filters required to limit the incoming energy to desirable wavelengths. These remaining components are summarized below by examining three potential setups for measuring pan temperature with IR:

- Sensing through the glass ceramic
- Sensing through a "window" inserted into the glass ceramic
- Sensing the side of the pan with a sensor above the cooktop surface

The first optical IR temperature system mentioned is mounted below the cooktop surface and 'sees' through the glass ceramic in order to measure pan temperature. In this case, the ceramic glass acts like a filter and limits the wavelengths that can be detected by any sensor mounted below the glass. Figure 4.7 shows a typical glass ceramic used in cooktop applications. These glass ceramics are designed to transmit the infrared energy produced by the heating elements – because of the high operating temperature of the heating elements the glass ceramic has been designed to transmit in the regions from about 1 µm to 2.7 µm.



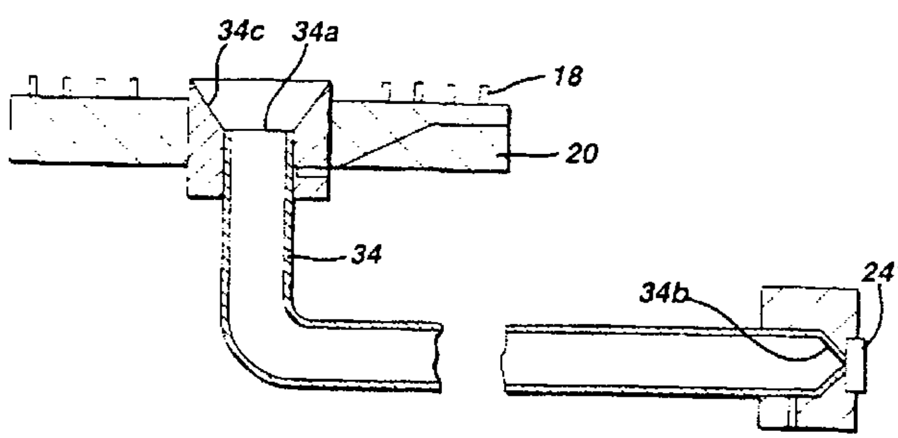
Source: U.S. Patent 6,118,105 (with IR Sensor Locations Added)

Figure 4.8: Optical Temperature Sensing System and Potential Optical Sensor Locations

The ceramic glass does transmit in wavelengths that are relevant to pan ignition temperatures. The transmission band between approximately 3.4 µm and 4.2 µm does transmit in wavelengths relevant to oil ignition temperatures, since a blackbody at 750°F emits peak energy at 4.3 µm. Some energy from a pan at oil ignition may be measurable from approximately 2.5 μm to 2.7 μm. Dual wave IR sensing may be possible through the ceramic glass, although no specific references to temperature measurement through ceramic glass were found in the literature.

A possible setup for this system can be envisioned by examining a figure from a General Electric patent that includes IR sensing. This patent is primarily concerned with measuring the temperature of the bottom of the glass and using this information to infer a boil state. However, they do mention the possibility of sensing the pan temperature by examining incident radiation in wavelengths that can transmit through the ceramic glass.

In this setup, the IR sensor 24 is located below the heating element or to the side of the heating element. The IR sensor in the center rests below a hole in the middle of the heating element. The IR sensor on the side rests at the end of a waveguide, which is an element that transmits the radiation emitted through the glass to a sensor outside of the heating element. The sensor locations and any lenses or waveguides, if needed, are designed to transmit enough infrared energy to the sensor so that it meets a required sensitivity for the given application. Lenses may not be needed depending on the amount of incident radiation and the sensitivity of the detector – a simple transparent cover over a sensor placed close to the object to be sensed may receive enough energy to calculate the temperature of the pot or pan. As illustrated in Figure 4.9, the inlet and outlet of the waveguide can be designed to receive and focus as much incident radiation as possible on the IR sensor, shown as 24' in Figure 4.9. General trends in lenses and covers are reduced cost with increased transmission over a variety of IR wavelengths.



Source U S Patent 6,118,105

Figure 4.9: Optical Temperature Sensing System and Associated Optics to Transfer IR Energy to Sensor. Sapphire (Al2O3) is One Potential Waveguide That Could Transfer IR to a Remotely Located Sensor

The second IR temperature system mentioned is one that 'sees' through a window inserted into the glass ceramic. A 'window' of quartz, soda lime glass, sapphire, silicon, calcium fluoride, and other materials could conceivably be placed in the ceramic glass.

The advantage of a window is that higher transmissivity increases the amount of IR energy transferred to the sensor, which increases sensitivity. A window system would not be limited to the transmission bands of the ceramic glass.

This system requires a hole in the ceramic glass over the heating element. The hole could be created before or after the ceramic glass is produced by the ceramic glass manufacturer. If the holes are drilled after the glass is formed, very precise tooling is required to insure that the glass is not damaged in the drilling process. The window materials have much larger coefficients of thermal expansion, so these materials would need to be potted with a high temperature silicone or other high temperature potting material. As an example, the coefficient of thermal expansion for typical ceramic glasses is on the order of 0.1×10^{-6}. Potential window materials such as sapphire and calcium fluoride have coefficients of thermal expansion on the order of 5×10^{-6} and 19×10^{-6}, respectively. These potting materials will not endure long-term in temperatures in excess of 450°F - 500°F, so the heating element would be required to have a dead zone in the area of the window.

Adding holes to the cooktop decreases the strength of the glass and creates a potential for ceramic glass failure. Ceramic glass can fail under extreme temperature gradients and can break under impacts from large objects. Current electric cooktops must survive the thermal shock test and the impact test as described in the standard UL 858.

The drilling and potting operations would increase the cost of the ceramic glass component, although the primary cost driver in this system would be the infrared detection system itself.

The third IR temperature system elevates above the cooktop and senses pan temperature on the side. This system is essentially the same as the second type of system mentioned above, except that the optical system needs to elevate above the cooktop in order to see the side of the pan and direct the IR energy to the IR sensor.

Bosch has produced this type of system for the European market. In this system, a sensor telescopes above the cooktop during cooking and receives radiation from special pans that have a high and constant emissivity strip on the lower portion of the pan. [Babyak] Food temperature control is possible, and the system can detect and shut down the cooktop in a boil-dry condition. The major limitation with this system is that specific pans with the strip of known emissivity must be used for the system to function. Food splatter or other dirt could also block the IR receiving lens and prevent the system from measuring a temperature.

4.3.1.2 Potential to Reduce Cooking Fires

The glass ceramic does transmit in wavelengths that are relevant to oil ignition temperatures. However, there are no references in the literature to using this approach to distinguish a safe pan temperature from an unsafe pan temperature. A safety determination of this type will likely require an absolute pan temperature, which is a challenging requirement. However, the properties of the ceramic glass indicate that an absolute pan temperature measurement may be achievable. The threshold safety levels for pan temperature are measurable within the transmission bands of the ceramic glass. Cooler pans are unlikely to emit any measurable IR because the ceramic glass is opaque to the longer wavelength IR associated with these temperatures.

A system with a properly chosen 'window' of transmissive glass would have higher sensitivity because more of the energy is transferred compared to the ceramic glass.

4.3.1.3 Development Needs and Issues

Additional efforts are required to determine whether dual wavelength IR sensors can determine pan temperature through ceramic glass. Inserting a 'window' into the ceramic glass would present many manufacturing difficulties and possible aesthetics and cleanability issues. Cost, durability, and reliability over the lifetime of a consumer product are a concern with any optical system.

4.3.2 Other Direct, Non-Contact Temperature Sensing

Laser interferometry and phosphorescence are two additional technologies found in the literature review. In particular, the thermographic-phosphor temperature measurement system has dozens of references for temperature sensing in aerospace, automotive, and metal industries.

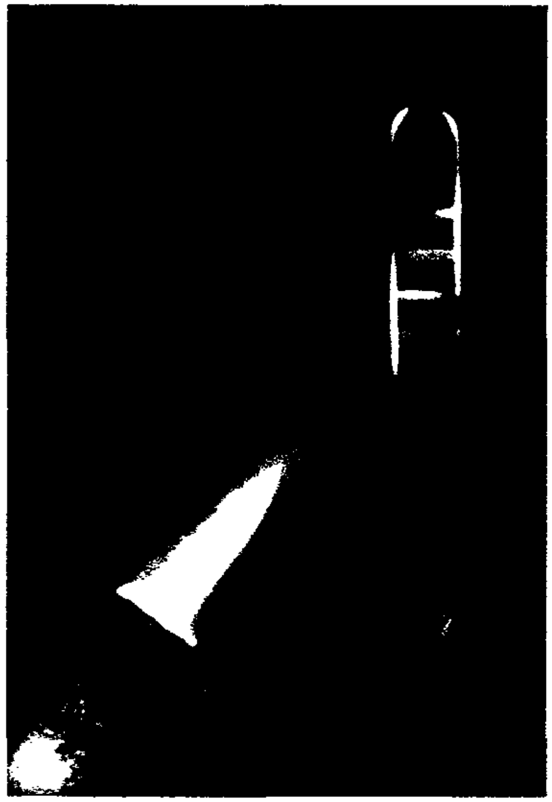
4.3.2.1 Laser Interferometry

Mechanical vibrations can be generated on a material and measured without contact by using extremely precise laser interferometry. [Kubyshkin et al.] A pulsed laser creates the surface acoustic waves. Possibilities for high temperature materials characterization are discussed in the reference cited by Kubyshkin et al. The optical system required to perform laser interferometry is extremely sensitive to the position of the target and the required optics. This technology is in its infancy and is currently laboratory based. A significant amount of development effort is required to miniaturize this system, cost-reduce it, and test its feasibility for a cooktop application. Additionally, the surface acoustic wave propagation is material-type dependent and would require additional means to determine the type of pot on the cooktop.

4.3.2.2 Thermographic-Phosphor

Thermographic-phosphor temperature measurements were the subject of several dozen documents found in the literature search. A phosphor is an inorganic, white powder that is used in fluorescent lamps and can be inexpensively applied to a variety of materials. [Allison] The phosphors are typically chemical resistant and are typically not water soluble.

Thermographic-phosphor temperature sensing systems use a phosphor applied to some substrate, a laser in the ultraviolet wavelength (ultraviolet is common, but X-rays and electron beams are also used), and a photoelectric detector to measure light in wavelengths specific to a given phosphor. [Allison] The pulsed laser excites the phosphor, and the decay in light intensity over time indicates the absolute temperature of the object that is coated with phosphor powder. The wavelength of the emitted light is dependent on the phosphor, and wavelengths within the transparent area of the ceramic glass are possible. One advantage of the thermographic-phosphor method is that the emissivity of the material is not required to determine the temperature.



Source Oak Ridge National Laboratories. http://www.ornl.gov/phosphors/

Figure 4.10: Turbine Blade Illuminated with Ultraviolet Light and Subjected to a Propane Torch. The Red Bands are Phosphors.

Thermographic-phosphor temperature sensing was developed for high-temperature, non-contact temperature measurement in aerospace (e.g., turbine blade temperature measurement) and automotive (e.g., piston and valve temperature) applications. It has been developed to control the temperature of galvanneal steel processing, where infrared temperature measurement is difficult due to the low and changing emissivity of the zinc during the steel fabrication process. [Beshears et al.]

Thermographic-phosphor temperature sensing of the pan cannot be considered a near-term solution because it would require coatings on every pan. It is possible that the phosphors could be included in decorative silkscreening and used to infer the glass ceramic surface temperature. As examined earlier with the thin film thermocouples, a temperature measurement scheme for the top of the ceramic glass and associated algorithms to interpret the temperature signals could potentially be used to infer a pan temperature.

4.4 Indirect, Temperature Measurement

Measuring the temperature of components besides the pan can be used to infer pan temperature. Specifically, increasing temperatures in the heating element zone or increasing temperatures in the glass ceramic often correspond to increasing pan temperatures. A water boil-dry condition is one example where the temperature of the pan increases rapidly when the water is no longer present to evaporate and remove large amounts of energy with it. If the heating element and ceramic glass are operating below their maximum temperatures during active boiling, they will then increase in temperature during a boil-dry until the heating element reaches its prescribed temperature limit.

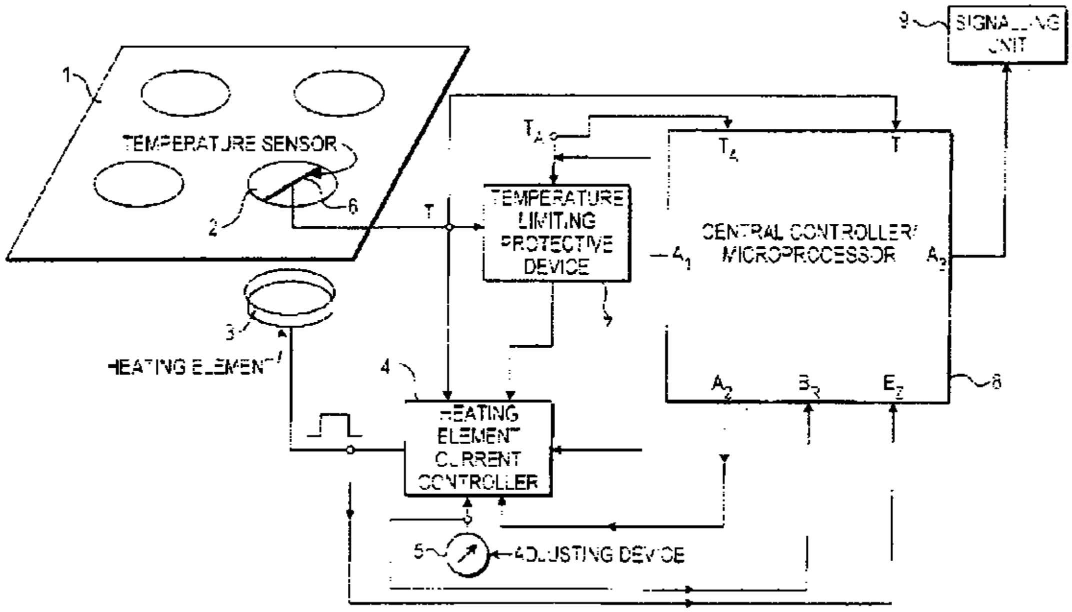
The literature has many references to surface temperature measurement. New methods for mounting temperature sensors directly to the top or bottom surface of glass ceramic are now available. Temperature sensors could also be mounted on the steel housing around heating elements, but because this steel housing encloses insulation there would be a lag time between an increase in temperature in the cooking zone and an increase in temperature on the outside of the element. Therefore, potential temperature measurement schemes in the cooking zone and on the bottom of the glass ceramic are discussed below. Possible uses for temperature measurement on the top of the glass ceramic were mentioned in Section 4.2 and are not repeated here.

4.4.1 Cooking Zone Temperature

All high temperature, infrared heating elements for glass ceramic cooktops have a temperature sensor embedded with them. Normally, this acts only as a switch to open the circuit after a certain threshold temperature is exceeded. The temperature of this sensor or of other temperature sensors on the bottom of the ceramic glass ceramic could potentially be used to detect over-temperature conditions.

4.4.1.1 Technology Description

Schott patent 6,300.606 lists three common cooktop scenarios associated with boil-dry conditions and potential means of sensing the boil dry. No mention of frying or other cooking mode control is made in the patent. This patent does not cover the specific types of temperature sensors that would be preferred in an application – these temperature sensors would be mounted on the heating element or on the underside of the ceramic glass as shown in Figure 4.11. This patent does focus on algorithms to detect a boil-dry condition for a smoothtop cooktop. It may be possible to extend the idea of measuring cooking zone temperature to infer pan temperature through pulsing of the heating element or other algorithms. [Rona et al.]



Source U S Patent 6,300,606

Figure 4.11: Schott Boil-Dry Temperature Sensing System

In the first scenario the cooking zone is operating well below the cutoff threshold temperature of the cooking zone. This could occur during a boiling cooking mode when a smooth and flat pan bottom is used. The combination of the large temperature difference between the heating element and the pan bottom and the good thermal contact between the pan and the glass leads to a low thermal resistance and a high heat transfer rate. In this case, a boil-dry is noticeable by looking at the change in cooking zone temperature over time along with the power input setting to insure that user changes are not simulating a boil-dry event. Figure 4.12 illustrates the temperature sensor response to a boil dry covered under this first scenario.

The second scenario is when the cooking zone is operating at the threshold temperature of the cooking zone. In this case, there is no temperature increase in the cooking zone during boil dry because the heating element input wattage is reduced such that the cooking zone temperature is maintained at the peak temperature. Schott claims that this decrease in heating element power can be used to detect a boil-dry condition and shut off the element.

The third scenario is when the cooking zone is operating within approximately 40°C of the threshold temperature. In this case, the temperature changes during a boil dry would be smaller and difficult to measure with this system. In this scenario, Schott re-sets the maximum steady state cooking zone temperature to a lower temperature. By doing this, changes in the power input to the cooking zone can be detected and use to infer a boil-dry condition.

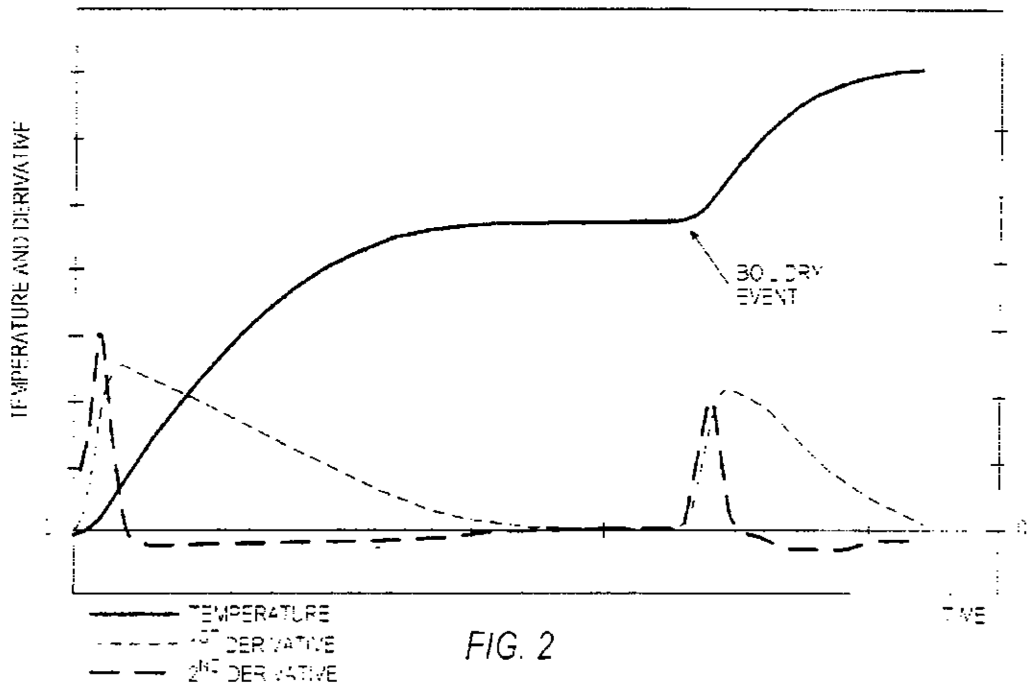


FIG. 2

Source: U.S. Patent 6,300,606

Figure 4.12: Temperature Sensor in the Cooking Zone Senses a Boil Dry Event for a Scenario Where the Cooking Zone is Operating Below the Allowable Threshold Temperature

4.4.1.2 Potential to Reduce Cooking Fires

The algorithms in the patent are limited to water boil-dry conditions, which represent a small fraction of cooktop fires. The algorithms as stated are not applicable to oil fires. Oil does not exhibit a phase change and the associated step-changes in heat transfer characteristics before hazardous temperatures are reached, so temperature and temperature derivative analyses are not useful in addressing oil pre-hazard conditions.

If cooking zone temperature or glass ceramic temperature can be correlated to absolute pan temperature, then this type of system could have potential to address cooking oil fires. However, it is not believed that the glass temperature can be used to indicate the absolute pan temperature due to variations in contact between the top surface of the glass and the pot.

4.4.1.3 Development Needs and Issues

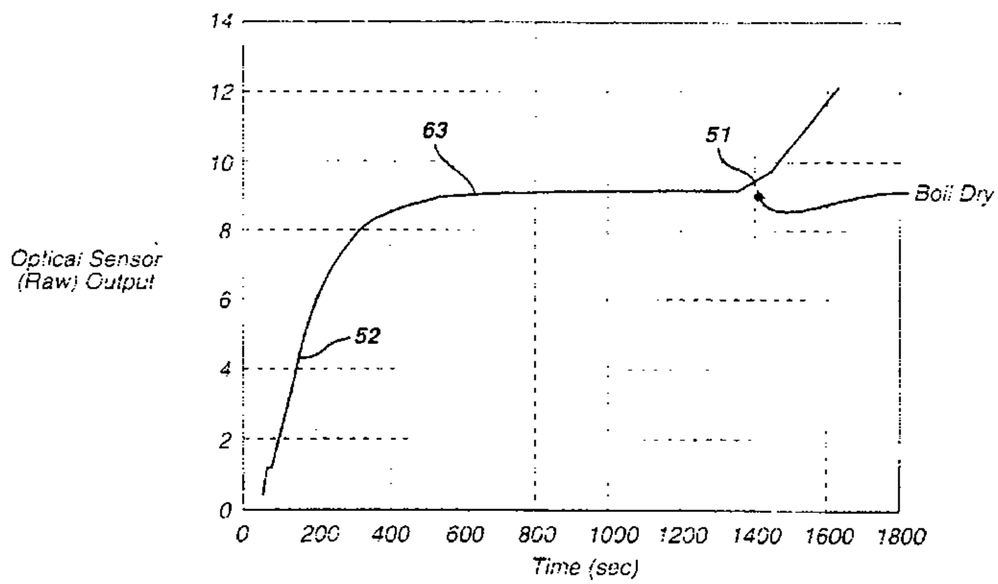
Further algorithm development and testing would be required to determine if this system could correlate a cooking zone temperature with pan temperature.

4.4.2 Glass Ceramic Temperature, Bottom

Thick and thin film temperature sensors as described previously could be applied to the bottom of the glass ceramic. Optical systems can also be used to measure the bottom temperature of the glass. In an optical system, wavelengths to which the glass is opaque may be used so that IR radiation from the other side of the glass ceramic will not distort the results. Appropriate filters also need to be designed to prevent temperature measurement error due to IR energy from the heating element.

Thin film and optical temperature sensors provide an opportunity to sense the glass temperature and infer the temperature of the pan above the glass ceramic. Sensors distributed radially or arrayed over the cooking zone could possibly determine areas where the pan is contacting the glass and use this information to more closely infer pan temperature.

Temperature sensing of the bottom of glass ceramic is proposed in a General Electric patent on boil-control. This system looks at the derivative of the temperature signal and infers a boil-dry from a sudden jump in temperature. In this case an optical IR sensor is used instead of a contact sensor – either means is possible. Figure 4.13 shows how output from an optical IR sensor can determine a boil dry condition.



Source U.S. Patent 6,118,105

Figure 4.13: Optical IR Sensor Showing Bottom Glass Temperature During Boil-Dry Condition

4.4.2.1 Potential to Reduce Cooking Fires

Thin film thermocouple or optical IR temperature sensing of the bottom of the ceramic glass offers opportunities to infer pan temperature. The response time of this system will be slower than temperature sensors on the top of the ceramic glass as outlined in Section 4.2 due to the low thermal conductivity value of the glass. However, multiple temperature sensors that can locate contact areas might give a closer approximation of absolute pan temperature.

4.4.2.2 Development Needs and Issues

Additional research and development in sensor selection, sensor location within the cooking zone or on the bottom of the ceramic glass, and algorithm development are needed to determine if this approach can infer pan temperature and determine an unsafe threshold temperature. Thin film and optical temperature sensing of the bottom of the ceramic glass have not been publicly demonstrated in any smoothtop to date. Durability, reliability, and cost of these systems will need to be addressed.

4.5 Indirect, Other Methods

This class of technology as currently described in the literature detects acoustic and other signals from the cooking process to indicate the boil state of cooking pan contents.

4.5.1 Acoustic

This technology has been applied exclusively to the detection of boil-dry conditions in the patent literature to date. The potential application of acoustic sensing to frying is also discussed.

4.5.1.1 Technology Description

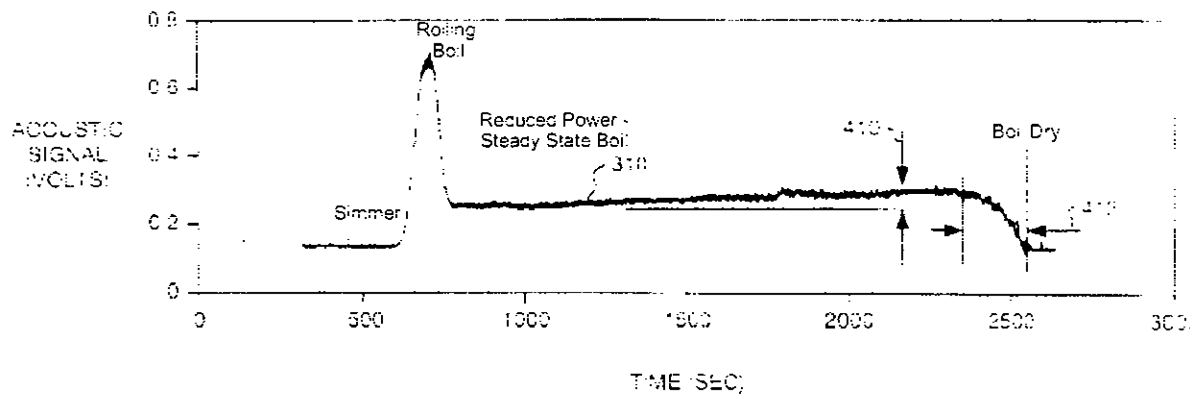
General Electric Patents 6,118,104 and 6,236,025 describe the use of acoustic signatures from cooking to determine the boil-state of water on a range top. These acoustic signatures are measured with sensors such as microphones, piezoelectric sensors and micro-mechanical sensor (MEMS) based accelerometers. An appropriately filtered and processed signal is used by the controller to determine a pre-simmer, simmer, boil, boil-over, or boil-dry condition. The latter patent specifically mentions induction heaters, gas burners, radiant heating elements used in ceramic cooktops, and microwaves as potential heating sources that are usable with this technology. Rice cookers, coffee makers, and crock-pots are listed as additional potential applications.

The frequencies of interest vary from 200 Hz to 8000 Hz. The frequency range sensed, the filters, and the signal processing have reportedly been selected to accept a multitude of cooking utensils, water fill levels, and user actions, such as stirring, without compromising performance. The acoustic sensor can also be placed away from the heating zone by using a waveguide to transmit the mechanical vibrations to locations away from the heat source. In this manner, a single acoustic sensor could sense multiple heating zones, presenting possible cost-savings to a manufacturer.

The controller mentioned in the patent can either notify the user that a particular boil state has been reached or actively control the system by, for example, reducing heat input after a rolling-boil is reached to prevent boil-over. The latter patent also specifically mentions that user input (e.g., position of the knob) and temperature measurements of the glass ceramic, pan temperature, cooking utensil content temperature can be used to complement the acoustic boil state detection system. As an example of a potential false alarm, the user can reduce the heat input to a cooking zone and stop the boiling process.

which the controller could see as a boil-dry situation if it only looks at the sound generated by the cooking process.

The primary fire-prevention capability is the ability to detect a boil-dry situation and turn off the appropriate heating element. The sensor is able to determine this by looking at the acoustic signature and its derivative over time. Figure 4.14 shows a representative example of the acoustic signature of a pan in a boil-dry situation. The pan starts off at room temperature at time zero. A simmer state is reached before the spike in the plot, which represents a rolling boil. The power input to the heating element is reduced, and the acoustic signal shows a gradual increase in time until boil-dry occurs at approximately 2500 seconds.



Source U.S. Patent 6,118,104 (with Boil Phases Added)

Figure 4.14: Change in Acoustic Signal from Start of Boiling to Boil-Dry

4.5.1.2 Potential to Reduce Cooking Fires

Acoustic sensing systems as currently described are limited to boiling control and boil-dry protection. No mention in any of the patents is made to detection or control of higher temperature cooking processes, such as sauté, searing, or pan-frying.

The ability of this system to detect a boil-dry does appear to be high, but the exact implementation of this system on a product and consumer acceptance are unknowns. It is believed that this is an enabling technology for pre-defined cooking modes on a cooktop. As examples, simmers for sauces and boiling modes for pasta cooking are potential cooking modes that could use this technology.

Continued development will be required to determine system reliability in detecting and controlling boiling modes of cooking. If the system is easily false alarmed and cannot reliably distinguish a true boil-dry from various user interactions (such as adding more cold water or frozen foods to a boiling pot), then consumers will not favor a system that has the capability to shut down in a perceived boil-dry condition.

These systems do have the advantage of being totally hidden and do not require any user interaction for their proper function. No reduction in cooking times or modifications to the cooking process are required. Enhanced user features such as pre-programmed boiling modes may be possible.

Acoustic signal detection should be applicable to deep-fat frying processes as well, since the frying process does create a significant amount of noise. The rapid heating and evaporation of water in fried food is very noticeable in a deep-fat fryer. The water released into the oil and evaporated does decrease with cooking time, but the acoustic signature should not disappear completely since no frying process eliminates all of the water from the food.

The largest problem with a "frying" mode is that the acoustic signature cannot be used to control the temperature of the oil. A system could be designed such that a "frying" mode is selected that doesn't control temperature. The system could shut-down after a certain number of minutes on a high power setting if no noise is detected (the acoustic signature of food means that the evaporation of water is absorbing large amounts of energy and generally keeping the oil within a safe temperature range). The system could also shut down once the food is removed (as represented by the sudden loss of an acoustic signature). The system could conceivably shut down if the food is forgotten and left on the heating zone too long (as represented by a gradual drop in acoustic signature as nearly all of the water is removed from the frying food).

One possible sensor fusion system would be to combine an adult proximity sensor with acoustic detection during a frying mode or whenever a cooktop element is set to its highest power levels and is not in a boiling mode. The acoustic signal could possibly sense that a mode other than boiling water is being used. If this is the case and if the heating element is set on high, a proximity sensor that detects an adult could be included that would shut down the element after the adult is absent for a small amount of time. Because so many frying fires start within 15 minutes of an adult leaving the kitchen, it is important to limit the amount of time that an element can be on high power if a boiling mode is not being used. [Smith et al.] As mentioned in Arthur D. Little's previous report, consumer acceptance of such a system is not guaranteed.

4.5.1.3 Development Needs and Issues

The acoustic sensing systems were not primarily designed as cooktop safety systems, and no safety claims are made in the patents. However, if the system can distinguish between user interactions that could create a false alarm (e.g., adding cold water), then the main question is whether the acoustic sensors can perform reliably over the life of the product. Inexpensive acoustic sensors are available, and this could be one of the lowest cost options at sensing boil-dry conditions.

Consumer acceptance for controlled surface cooking modes is unknown. The possibility of preventing fires from deep-fat frying by detecting the acoustic signature of various fried foods needs to be explored in further detail. It is possible that a "frying" mode without temperature control could detect hazardous conditions associated with a cooking fire.

4.5.2 Power Consumption Information

Power consumption information cannot detect a potential hazard by itself. Power consumption information is considered as a part of a sensor fusion system that would increase the performance and reduce false alarms in other systems mentioned in this report. The Schott and General Electric patents all consider power consumption information to improve system performance by reducing false alarms.

4.6 Combined Systems

Combined systems represent the fusion of one or more of the sensor technologies listed above. The primary gains from sensor fusion are increased performance and reduced cost.

4.6.1.1 Technology Description

General Electric patent 6,301,521 describes a sensor fusion system that uses acoustic sensors, temperature sensors, timers, power level settings, optical sensors, and strain gauges to determine many characteristics of the cooking food and cooking pan. The acoustic, temperature, timer, and power level setting sensors have been described in previous applications. The strain gauges and optical sensors are mentioned as possible means to determine the cooking load on the heating element.

This patent is a boil control method and not a safety device. It will detect a boil-dry condition, but it is not designed to determine unsafe temperature levels for frying and other high temperature surface cooking modes.

4.6.1.2 Potential to Reduce Cooking Fires

As mentioned previously, boil-dry is a small percentage of surface cooking fires. This technology appears to control the boil-state very well. If system performance is high and can be implemented for a low cost, it may be feasible to offer this option to consumers in the near future. Boil-dry control systems may pave the way for possible sensor-based cooking mode control systems for other cooktop cooking modes such as frying.

Applying multiple sensors to more accurately infer the higher pan temperatures associated with frying did not show up in the literature search. The combination of cooking zone sensors with optical IR sensing of the cooking pan needs further examination to determine the optimum sensor configuration for determining when a pan has reached an unsafe threshold.

4.6.1.3 Development Needs and Issues

The selection of the appropriate sensors and algorithm development to detect a threshold unsafe condition are continued needs in addressing cooking fires from deep fat frying.

4.7 Cross-Over Technologies

It is preferable that any pot temperature sensor system be applicable to open-coil electric ranges and gas cooktops in addition to glass ceramic cooktops. Cross-platform operability increases sales volumes (with corresponding reduction in sensor system costs) and increases the potential positive impact of a given safety system.

The acoustic sensing systems mentioned above are being considered for use in open-coil ranges and gas cooktops according to the patent literature. The other technologies mentioned in this report are generally not applicable to the open-coil electric and gas cooktop because less expensive alternatives have already been demonstrated.

Contact thermocouples are less expensive and more easily integrated into the gas and open-coil electric cooktops than the more expensive and less developed resonant temperature sensors, thin film thermocouples, thermographic phosphor method, and laser interferometry method. Contact temperature sensing works with pots and pans made of different materials, but optical infrared temperature sensing is extremely dependent on the emissivity of the object, which varies by pot or pan material.

4.8 Summary of Technologies

Cooking modes responsible for surface cooking fires and user behavior must be considered when evaluating these technologies. The sensor technologies must address the dominant problem of deep-fat frying cooking fires before any questions of reliability, durability, operability, and cost factors are considered.

4.8.1 Pre-Hazard Conditions

User behavior must be considered when evaluating safety systems for cooktops. Cooking processes used, types of food cooked, and other operator behaviors play a role in cooktop fires. [Smith et al., Arthur D. Little] For example, in the majority of cooking fires examined by the CPSC, the operator was not present at the time of the fire. [Smith et al.] In addition, the majority of fires associated with frying occurred within 15 minutes of the user leaving the kitchen.

It is not surprising that deep-fat frying fires can start so quickly. The specific heat of oil is approximately half that of water, so heat-up times for oil are much faster than the heat-up times for an equivalent volume of water. Oil does not change phase before ignition, so there is no way for the oil to lose heat except through radiation and natural convection. The ceramic glass has a high heat capacity, so the heating element needs to be shut off before unsafe temperatures are reached to prevent additional heating of the oil. Only the presence of food in the oil and the associated boiling off of the food's water content will keep oil temperatures below ignition temperatures.

Pan temperature sensing is therefore critical in any cooktop safety system. A system that shuts down only when the pan is hot enough to start a fire would avoid many of the false alarms that would occur in a proximity system.

Frying is the cooking mode associated with the most fire incidents. [Smith et al.] Therefore, any safety system should consider the pre-hazard conditions for a frying mode induced fire. Some possible pre-hazard conditions include:

- Pan with cooking oil, heat on, no food inserted into oil (runaway condition – oil overheats and ignites)
- Pan with cooking oil, heat on, food inserted into oil (if the food mass is small relative to the oil mass, hot spots or a runaway condition could still occur)
- Pan with cooking oil, heat on, food removed and heater remains on (food absorbs a tremendous amount of heat because of the energy required to heat and evaporate water, so any food removed will lead to a sharp spike in oil temperature)
- Spilled grease ignites around hot ceramic glass (if the pan diameter is smaller than the diameter of the heating element)

Frying is also the most difficult cooking mode to manage. The difference between safe frying and dangerous temperature levels is small, and the time required to go from a safe to a dangerous situation can be a matter of minutes or less. The higher operating conditions put the pan temperature closer to oil ignition temperatures, as shown in Appendix A. The ceramic glass may reach a temperature above the ignition of oil, so oil splatter could be an ignition source on glass ceramic cooktops. Appendix A also shows that most oil fires occur within the first 15 minutes of cooking. However, because of the short times associated with many frying operations, any of the four pre-hazard conditions above could occur within the first 15 minutes. The last pre-hazard condition is not addressable with a pan temperature detection system.

4.8.2 Summary of Listed Technologies

The technologies that show some promise are those that are able to directly measure pan temperature through contact or non-contact means. These technologies are:

- Optical IR systems that look through the ceramic glass or through an inserted window
- Contact temperature sensors mounted to the surface of the glass
- Combinations of other sensors that are able to infer pan temperature by looking at the temperature of the bottom of the ceramic glass

Additionally, acoustic sensing does show promise for deep fat frying because of the noise produced in this process. However, acoustic emissions are not believed to be an indication of oil temperature, so acoustic sensing may need to be combined with proximity or temperature sensors for maximum benefit.

Optical IR systems could look at multiple wavelengths to determine pan temperature without knowing the emissivity of the pan. Further evaluation is required to understand the full limitations of such a system.

Thin-film thermocouples, surface acoustic wave sensors, and thermographic phosphors offer the potential to measure ceramic glass surface temperature. Further work is required to determine their suitability for the ceramic glass cooktop surface and to determine the types of algorithms that may be needed to infer pan temperature from the sensor output.

Combinations of sensors, such as temperature sensors in the cooking zone and IR sensors looking at the pan, could possibly determine the pan temperature more accurately than one of these sensors in a stand-alone application.

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6. Appendix A: Pre-Hazard Conditions for Cooktop Fires

In previous work, Arthur D. Little identified pan content temperature and pan bottom temperature during normal cooking operations and in cooktop fire conditions. Those temperature bands are shown below in Figures A-1 and A-2. [Arthur D. Little]

These results show that any pan temperature monitoring system needs to distinguish between high temperature frying and oil ignition temperatures in order to reduce false alarms.

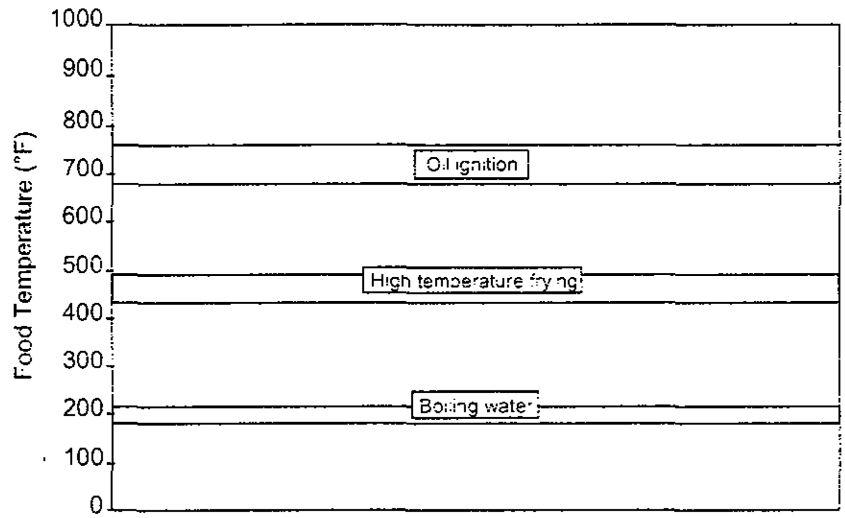

Figure A-1: Temperature of pan contents during various cooking procedures

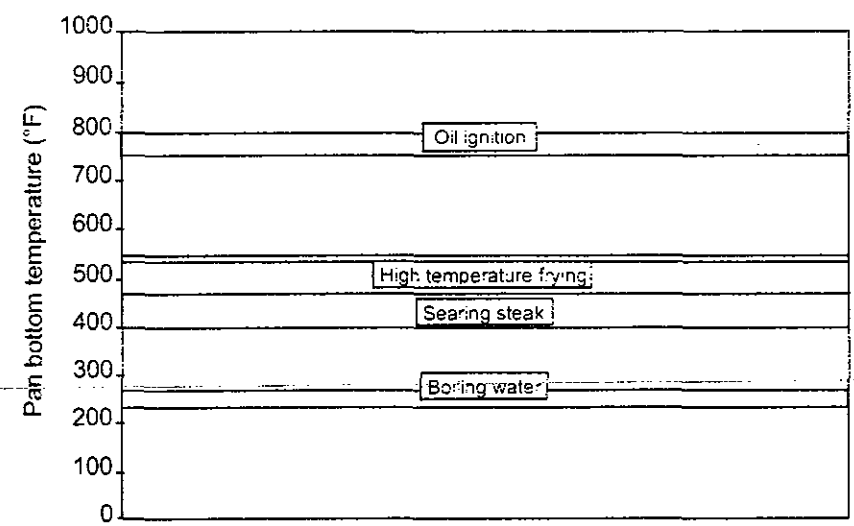

Figure A-2: Temperature of pan bottom (at center of pan) during various cooking procedures

7. Appendix B: Literature Search

The following literature databases were searched in order to understand how non-contact temperature measurement is used in different industries. Several searches were performed using various combinations of keywords. The literature search results are provided on an attached diskette. The databases examined in each search include selections from the following:

Aerospace: AEO
Agricola: AGR
Biological Abstracts: BIO
British Library Inside Database: TO1
CA Search (97-99): CA1
CAS - Combined Divisions: CAS
Ceramics (CER): CER
Chemical Engineering Abstracts (CEA): CEA
Conference Papers Index: CPI
Dissertation Abstracts: DIS
DTIC: DOD
Energy Science and Technology (DOE): EDB
Engineered Materials Abstracts (EMA): EMA
Engineering Index: EIX
European Patent Applications: EPA
European Patent Granted: EPB
Federal Research in Progress (FRP): FRP
Food Science & Tech. Abstracts (FSTA): FST
Geological Abstracts (GEOREF): GEO
Grey Literature in Europe: SGL
Inside Conferences: CON
Inspec: INS
Mechanical Engineering (ISMEC): ISM
Metals Abstracts (ASM): ASM
NASA Star: NAS
Paperchem: IPC
Patent Abstracts of Japan: PAJ
PCT Database: PCT
Physics (SPIN): SPN
RSC Analytical Abstract: AAN
Rubber & Plastics Research Abstracts: RPA
U.S. Patent Bibliographic Database: PAT
USG/NTIS: USG
World Ceramic Abstracts: WCA