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Development of a non-contact Temperature Measurement Device for Lexmark Laser Printer

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Appendix D - UNIVERSITY HONORS PROGRAM
SENIOR PROJECT - APPROVAL

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PROJECT TITLE: Development of a Non-Contact Temperature Measurement Device for Lexmark Laser Printer

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

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Comments (Optional):

Non-Contact Temperature Measurement of a Printer Fuser Assembly

Julie Paddleford, Mechanical Engineering
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The sponsor company, Lexmark, wanted to examine the possibility of a non-contact method of measuring the temperature of the hot roller fuser assembly in their low end laser printer. The current method involves a thermistor mounted on a thin film which contacts the roller. This contact leads to premature wear of the roller and the buildup of impurities under the film. By finding a way to make the measurement remotely, the life of the roller could be extended such that it would match the life of the printer; thus eliminating three changes of the roller assembly.

The primary limitations in the design were size, effectiveness, and cost. This eliminated such choices as fiber optics and photoconductive infrared detectors. The design should be as small as possible and require few modifications to the current cover and assembly. Effectiveness is determined by the following: The measurement design should be ablr to control the fuser assembly lamp such that the aluminum roller can be held at a nominal temperature +/- 5. The final design of a thermistor based bolometer was chosen. A bolometer is a configuration of two thermistors connected in a bridge circuit. One thermistor is Active and the other is the shielded or "compensating" thermistor. This shielded thermistor accounts for changes in the ambient temperature as the roller assembly is in use.

At this point it appears that the bolometer will produce acceptable results. By manipulating the data after collection we were able to obtain a reasonable degree of certainty regarding the temperature reading. The data manipulation consists of taking the log of the ratios of the resistances from the two thermistor. Currently we are trying to find a circuit that will perform this transformation in the hardware, rather than the software, to ease the implementation of the design into production.

Lexmark Thermal Design Group

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OBJECTIVE

Lexmark Inc. has requested the design of a non-contact temperature sensor for the fuser assembly on Model 4059, a low end laser printer. This report describes the approach taken in the problem definition and outline of design parameters, the design of a detector suitable to operate within these parameters, and the results from the implementation and testing of this detector.

MOTIVATION

A fuser assembly is the last part of a laser printer which the paper passes through. The purpose of the fuser is to permanently bond the toner particles to the paper. The fusion of the toner is accomplished by heating the paper and toner to a high temperature, applying a force, and retaining that force for a given time. These three factors, temperature, force, and retention time, all affect the final print quality. The heat is supplied from a heat source within the hot roll, the force is supplied by a stiff spring holding a soft roll in contact with the hot roll, and the retention time is determined by the speed at which the hot roll rotates.

Accurate and reliable temperature control of the hot roll is imperative to ensure high print quality. The current sensor employed by Lexmark is a thermistor mounted on a film which is in direct contact with the hot roll. The temperature reading and print quality are adversely affected as abrasive particles of toner collect under the thermistor assembly. This causes two problems in the printer: the particles tend to cause a thermal resistance between the thermistor assembly and roll and thus adversely affect the temperature reading and the toner particles tend to wear through the Teflon coating covering the roll which diminishes the print quality. A scaled drawing of the fuser assembly is shown below in Figure 1.

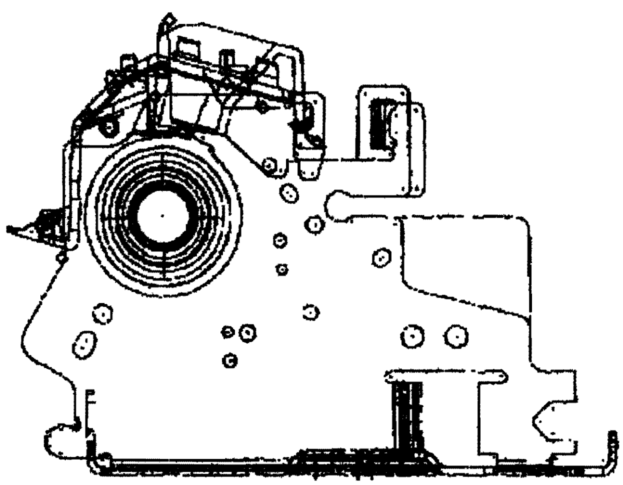

Figure 1: Fuser Assembly From Lexmark

PROBLEM STATEMENT

The objective was to design a non-contact temperature measurement device which could be used to accurately control the temperature of the hot roll at 180°C or 200°C. The effectiveness of the design is based on the detection device used,the geometry of the system, and the properties of the materials in the hot roll and assembly. The printer currently uses a Shibaura model PSB-S3 glass encapsulated thermistor mounted on a film to measure the temperature. The thermistor has a nominal resistance of 231.4 kΩ at 25°C and a β constant of 4240 K taken between 25 and 85°C. The time constant of this thermistor ranges from 3.5 to 6.5 seconds.

The hot roll is constructed of aluminum and it is covered with a Teflon coating. The roll diameter at the detector is 30.5 mm and the roll is saddle shaped to prevent paper curling. Heat is supplied to the roll through a 750 W, 110 V lamp enclosed within the hot roll. Heat is dissipated to the silicon rubber soft roll below, the wiper above, and to the paper which is passed through the fuser.

The desired roll temperature to ensure proper fusion is 200°C. Lexmark has defined a tolerance of +/- 6°C on this temperature. After operation, the printer goes into a standby power saving mode in which the roll temperature is held at 180°C with the same +/- 6°C tolerance. The lamp is operated using the temperature sensor as a derivative based controller. The lamp is on based on the rate of change of temperature, below the desired temperature, the lamp is off. To ensure proper printer performance, it is only necessary to provide a detector with known output at 180 and 200°C, and relative values of other temperatures. Emphasis will be placed on detector stability and signal strength at these two temperatures.

The two primary limiting factors in this design are cost of proposed design and size of overall design. The laser printer which this design is intended for is a low end model and the new design should not add to the base price of the printer. The proposed non-contact sensor will have the advantage of increasing roll life, which is approximately one-fourth that of the printer; 250,000 pages as compared to 1 million pages. By extending the life of the fuser assembly, some of the cost of the new detector will be absorbed. Die retooling will also be minimized. The current thermistor assembly costs $1.80 per assembly and the working cost limit for the design is $6.00.

The fuser assembly is placed in close proximity to other parts in the laser printer so that there is little room to extend outside the cover assembly currently on the fuser. The design will be able to extend no more than 4-5 millimeters outside the cover assembly.

The design of a suitable detector will be concerned with the following:

- Calibration at 180°C and 200°C, providing long term stability
- Obtaining a time constant equal to or less than that of the current thermistor
- A suitable sensitivity at 180°C and 200°C
- Repeatability of results through a range of ambient conditions

The design process began by identifying suitable detectors from which the recommended detector was selected on the basis of cost and size.

THEORETICAL STUDY

Heat is transferred from the surface of the hot roll through two phenomena, convection and radiation. The convection will cause a temperature gradient in the fluid surrounding the roll. The radiation, propagated as electromagnetic waves, may be partially absorbed in the fluid surrounding the roll, and therefore cause some temperature rise in the fluid. However, the absorption to the fluid in close proximity to the roll is low. The electromagnetic waves then act primarily to heat a surface which absorbs the waves and therefore the radiant energy associated with those waves.

The total heat transfer from the roll to the fluid can be expressed as the additive effect of the convective and radiant heat transfer, or

$$q = q_{conv} + q_{rad} \qquad (1)$$

The convection heat transfer can be expressed by Newton's law of cooling,

$$q = hA_s(T_s - T_a) \qquad (2)$$

In equation (2), A_s represents the surface area exposed to the fluid, T_s represents the surface temperature, and T_a represents the ambient temperature. In the case of the printer, there is no appreciable velocity over the surface of the roll. Therefore, the convection is termed free, or natural, convection. The convective heat transfer is caused by the buoyancy forces within the fluid. The buoyancy is due to "the combined presence of a fluid density gradient and a body force that is proportional to density" (Dewitt, 530).

In the instance of the cylinder exposed to free convection, a plume will form. With the temperature of the cylinder above that of the surroundings, the air at the surface of the cylinder will become less dense and buoyancy forces will tend to force the air up, causing free convection currents as indicated in Figure 2.

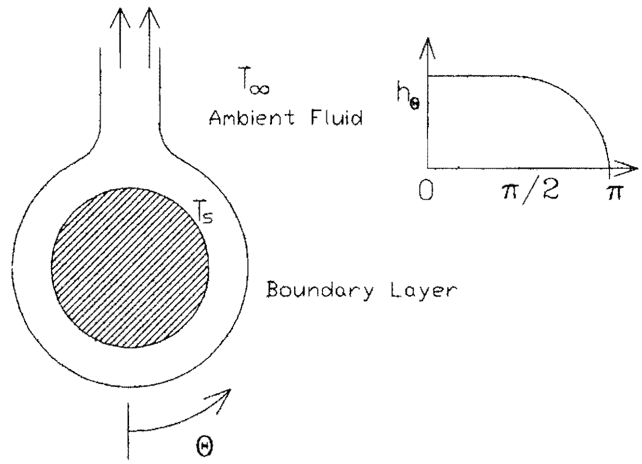

Figure 2: Plume

In the case of the printer, the formation of the plume will be adversely affected by the wiper covering the top surface of the roll. The flow will tend to circulate within the cavity formed between the cover assembly and roll.

The heat transfer coefficient, h, is determined by knowledge of the situation. In the instance of free convection from a cylinder, an average heat transfer coefficient can be determined from knowledge of the Grashof number. From considerations of the problem at hand, an average heat transfer coefficient, h, was found to be 11.07 W/m^2 K using Churchill and Chu's correlation as presented by Dewitt (Dewitt, 51). The calculations appear in Appendix A. Using the average value of h in Equation (1), the total convective heat transfer from the roll is found to be 45 W assuming an ambient temperature of 22.2°C. This is not the heat transfer which would be seen at a point. The actual value of h is directly proportional to the size of the plume at any point on the roll as seen in Figure 2. The value of h at a location suitable for placement of a detector would therefore be lower than the average calculated. The calculation of the heat transfer coefficient assumes a long cylinder, normal formation of a plume, and ignores conduction to the soft roll and wiper assembly.

The value of h depends on buoyancy forces caused by density gradients within the fluid. It is affected by the development of the velocity and thermal boundary layers. The velocity will be zero at the surface, maximize some distance form the surface, then return to zero at a point removed from the roll. The temperature will be a maximum at the surface and decrease with distance from the surface. The boundary layer is time dependent, and thus the temperature at any point removed from the roll, as induced by free convection, will be not only a function of the absolute temperature of the roll, but also of time. Therefore, relying on a sensor sensitive only to convection transfer would have inherent problems in stability.

The roll rotation will also act to increase the heat transfer coefficient. The rotation causes a centrifugal force which will act to increase the velocity gradient. This will result in mixed convection, and the effect of forced convection generally outweighs that due to free convection. In forced convection, the heat transfer coefficient is essentially independent of time, but is dependent on the velocity of the object. The roll rotates at a constant speed, so it is assumed that with rotation, the convection heat transfer can be assumed constant. The heat transfer coefficient will still vary with angle.

The other mode of heat transfer is radiation. The radiative heat transfer behaves according to the Stefan-Boltzmann law,

$$q_{rad} = \varepsilon_t \sigma A_s (T_s^4 - T_i^4) \qquad (3)$$

where σ is the Stefan Boltzmann constant, and ε_t is the total hemispherical emissivity of the roll. The emissivity may vary with both the angle from the surface in consideration to the detector and with the surface temperature, but does not vary with time. The radiation heat transfer from the roll, using $\varepsilon_t = 0.92$ for Teflon, as reported by Dewitt, is found to be 50 W. This calculation appears in Appendix A.

An expression for the radiative heat transfer from the roll, solely as a function of temperature, can be found and is of the form

$$q = \sigma F_g F_\varepsilon (T_s^4 - T_a^4) \qquad (4)$$

Which is the same as Equation (3) except ε_t is replaced by the factor F_g, which is added to show the dependence of emmittance on surface geometry, and the factor F_ε, which shows the dependence upon radiative properties of both detector and emitting surface. However, the surface and geometric conditions of the roll and detector should be constant over time (except for toner buildup on the roll, to be discussed later). The energy radiated between the surface and detector for a given temperature difference is predictable and repeatable.

Based on both the relative intensity of convective and radiative transfer, as well as the nature of both modes of heat transfer, the detector for the application was designated as one which will rely on the detection of radiation. The main factor in this decision is the presence of time dependent variables in the convection heat transfer. Over the considerably large range of operating conditions, the development of the boundary layers may change and cause errors in temperature measurement. On the other hand the amount of energy does not depend on time, but is solely temperature dependent.

IR THEORY

Emitted radiation takes the form of electromagnetic waves. The radiation emitted will vary with the absolute temperature of the roll. At any temperature, radiation is emitted throughout the IR spectrum. The relationship between radiation intensity, spectral distribution, and absolute temperature of a radiant source can be described by Planck's law. Planck's law for a blackbody, as reported by Hackforth, takes the form

$$q = c_1/\lambda^5(e^{c2/\lambda T} - 1) \qquad (5)$$

Thus, the radiance versus wavelength takes the form indicated in Figure 3.

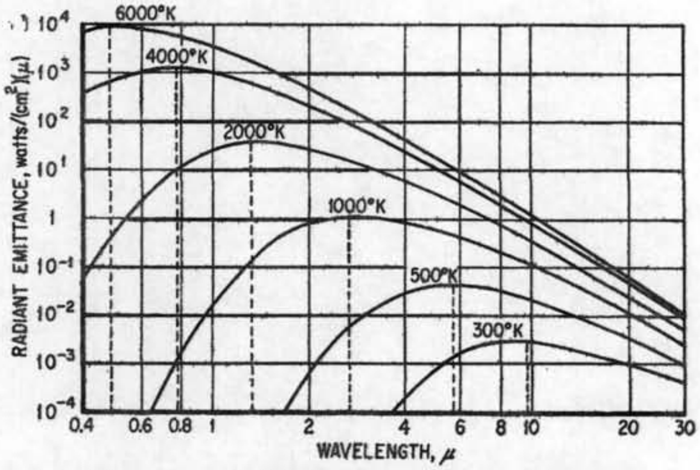

Figure 3: Blackbody Emittance, (Hackforth, p.16)

The wavelength of peak intensity, modified for a gray body, takes the form

$$\lambda_m = (2897\ \text{K})/\varepsilon_t T \qquad (6)$$

where the calculated wavelength is reported in microns. For the temperature of 200°C and emissivity of 0.92, the detector for this application will need a maximum sensitivity in the region near 6.66 μ. At 180°C, the wavelength of maximum intensity is 6.95 μ. This is within the Far IR region of the spectrum, which begins at 5.6μ. The actual roll will deviate from the gray body assumption because its emissivity will vary with wavelength. The total energy radiated throughout the IR spectrum can then be represented by

$$q = \int_0^\infty c_1/\varepsilon_\lambda \lambda^5(e^{c2/\lambda T} - 1) \qquad (7)$$

where ε_λ is the spectral emissivity. Applying this equation, the amount of radiation emitted at different wavelentghs will take a form similar to that shown in Figure 4.

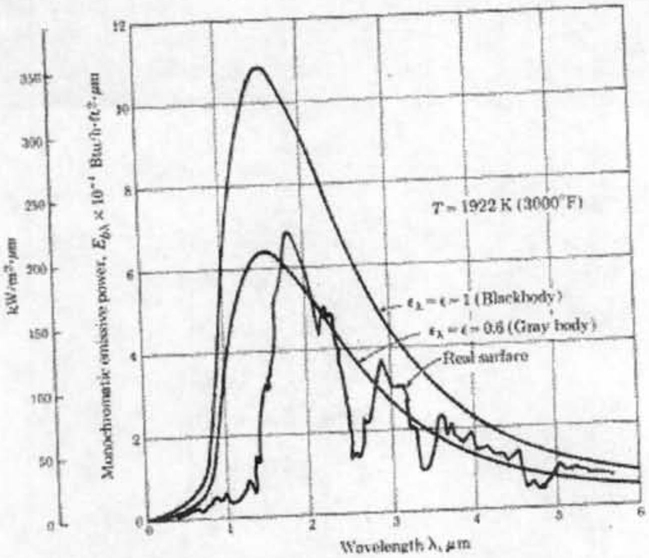

Figure 4: Blackbody vs Real Surface, (Holman, p.317)

This complicates computations to accurately detect the power received by the detector. Besides spectral emittance, there is also directional dependence. The emittance from a plane surface, corrected for angle between a normal to the surface and the detector, is expressed by Lambert's Law of Cosines, which is of the form

$$q_s = qA/2\pi d^2\cos\theta \qquad (8)$$

where q_s indicates the fraction of the total energy, q, which is received by the surface. The dependence of emittance on angle does not rigidly follow Lambert's Law of Cosines. The angle between the detector and surface should be kept below 45° for non-blackbody surfaces, and normal emissivity should be employed for emittance corrections (Harrison, 33).

The detector design is further complicated by the radiative properties of the detector itself. For the detector, a certain amount of the incident radiation is absorbed and a portion is reflected. The relative amounts sum to one, or

$$\alpha + \rho = 1 \qquad (9)$$

It is desirable to have an absorptivity of unity in a detector to obtain the maximum sensitivity. In thermal equilibrium, the emissivity of a surface is equal to its absorptivity. Therefore, a detector with a high emissivity is desired.

Determination of the actual spectral and directional properties of the radiation is beyond the scope of this project, and is not necessary in this case. According to Harrison,

> "In the automatic control of the temperature of imperfect radiators that are not so enclosed as to establish blackbody conditions, it is seldom necessary to take special account of the radiating characteristics of the objects being treated, since uniformity of the product rather than exact temperature measurement is the objective in these cases" (p. 6)

The problem at hand represents such a case. Although it is not necessary to determine the spectral and directional distribution of the radiant energy emitted from the roll surface, a fundamental understanding of the properties of radiation is imperative in the selection of a suitable detector. Also, the changes in the spectral emissivity and directional distribution of radiant energy as roll surface conditions change due to wear of the roll is a concern. This problem will be addressed during the testing problems by using worn rollers in a portion of the tests.

DESIGN CONSIDERATIONS

Measurement of radiant energy in the long wavelength Far IR region of the IR spectrum requires a detector and focusing means sensitive to radiation in those wavelengths. Suitable detectors are some photoconductive cells with detectivity up to approximately 8μ, and all thermal detectors. Photoconductive cells have the advantage of fast time constants in comparison with thermal detectors. Thermal detectors are both more rugged and more responsive to Far-IR radiation than are photo cells. The thermal detector also does not require mechanical chopping of incident radiation, which most photocells do. Also, thermal detectors can usually withstand higher operating temperatures than can photocells. The thermal detector is the best choice for the application at hand. Figure 5 indicates suitable detector choices based on the region of the IR spectrum under consideration.

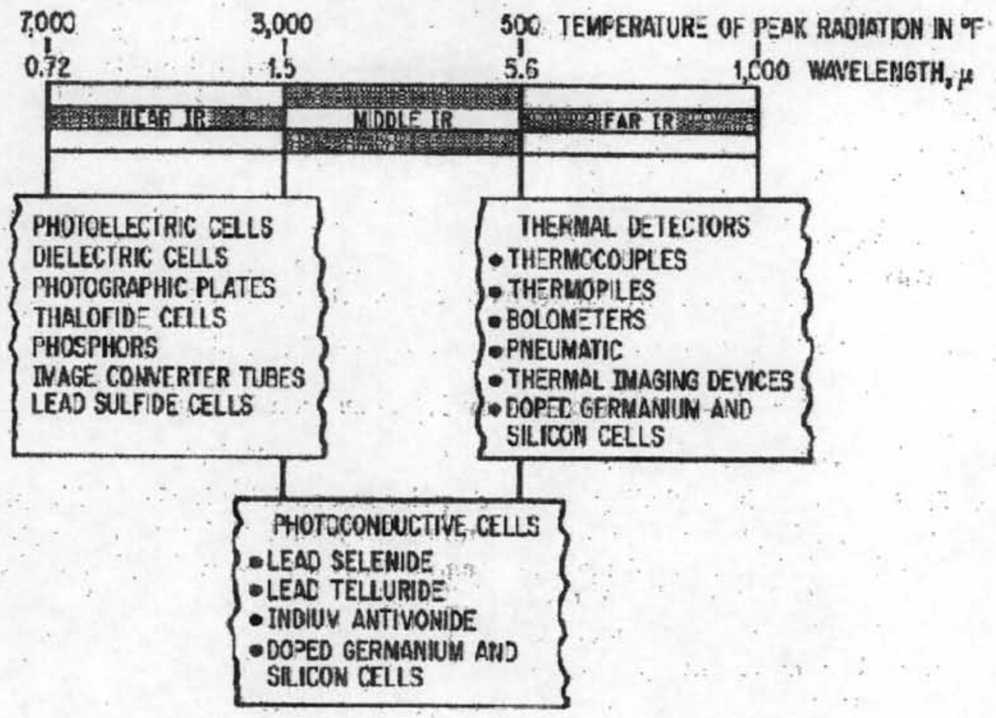

Figure 5: Infrared Detectors

As Figure 5 indicates, several suitable thermal detectors exist for measuring the far IR region. The most practical for this application being thermopiles and thermistor bolometers. A thermopile consists of several thermocouples arranged to be exposed to incident radiation. The reference junction of the thermocouple may be attached to the detector housing so that the detector output is proportional to the temperature difference between the housing and surface as indicated by the radiation received. Ambient compensation is generally not required in applications in which the housing temperature remains fairly constant.

A thermistor bolometer generally consists of two semiconductor flakes, or thermistors, enclosed in a sealed housing. The housing is covered with a window which passes IR radiation in the spectral region corresponding to the IR source temperature. The assembly is filled with an inert gas which likewise passes IR radiation in the spectral region of concern. The window and inert gas help reduce convection losses to the system surroundings.

One thermistor in the bolometer is exposed to incident radiation and is termed "active". The other thermistor is shielded from radiation and is referred to as the shielded thermistor. The thermistors are connected in such a way that the output is proportional to the difference between the resistance, and hence the temperatures, of the two thermistors. This means the output is of the form

$$V_{out} = f(\Delta T_{active} - \Delta T_{shielded}) = f(\Delta T_{amb} + \Delta T_{rad} - \Delta T_{amb})$$

$$V_{out} = f(\Delta T_{rad}) \qquad (10)$$

A schematic of a typical thermistor bolometer and typical bias circuit for reading the output appears in Figure 6

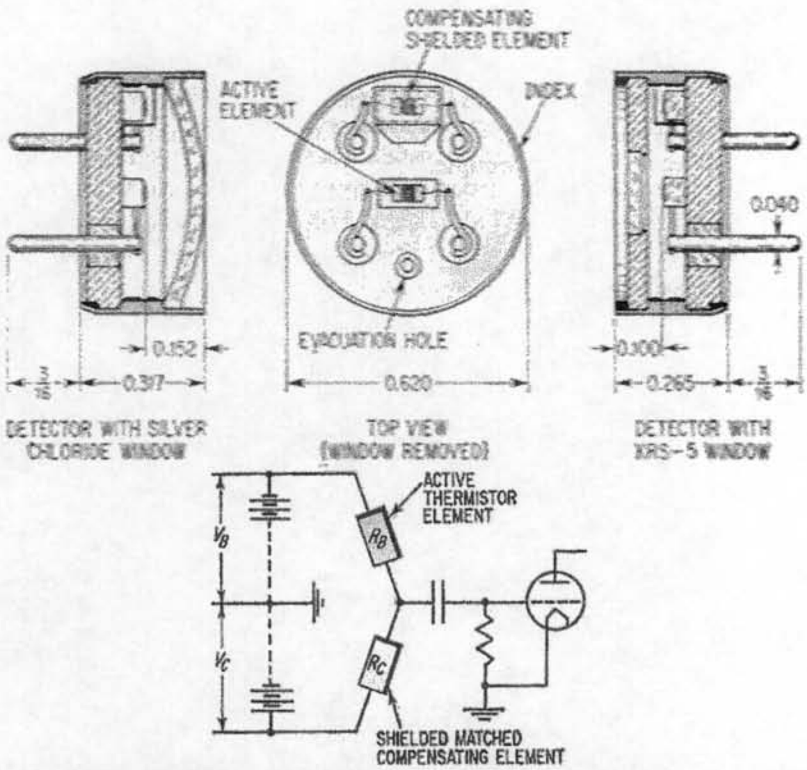

Figure 6: Thermistor Bolometer Circuit, (Hackforth, p.112)

The thermistor bolometer was chosen for use as the detector in this application. Its simplicity makes it ideal for this application. Commercially available bolometers are both too expensive and too large for use in this application. Examples of readily available detectors appear in Appendix B.

In order to resolve the excessive cost and size, a custom bolometer was designed, making the following modifications to the standard bolometer design:

- Removal of window
- Removal of inert gas
- Use of glass encapsulated thermistors

The window was removed to lower the detector cost. A calcium fluoride window is ideal for detectors for sources at 200°C. The least expensive thermal detector with a CaF window was $20, too expensive for the application. The removal of the window makes it impossible to seal the assembly to use an inert gas. Due to the limited space and lack of focusing lens, along with the geometry of the roll, the assembly must be placed close to the roll to detect a sufficient amount of radiation. Figure 7, showing the spectral absorption in air, indicates high absorption in the 6 to 8 μ region. Due to the close distance, the losses due to atmospheric absorption will therefore be insignificant.

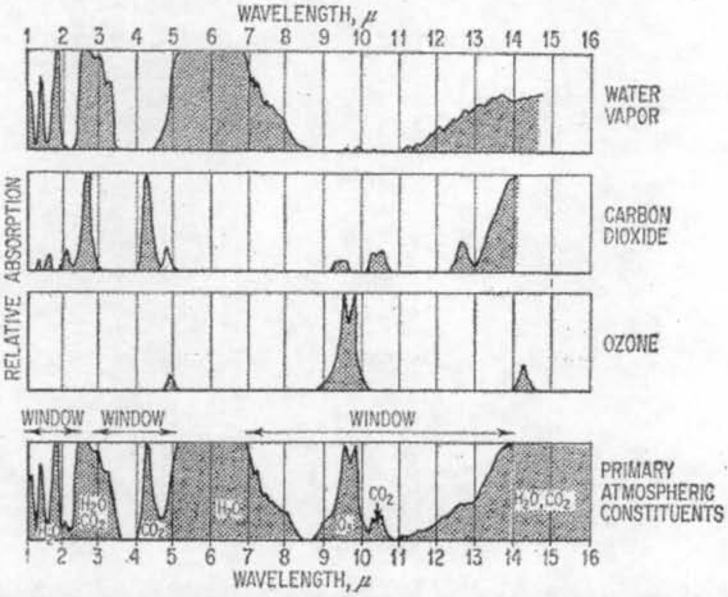

Figure 7: Relative Absorption vs Wavelength For Common Gases, (Hackforth, p.49)

The close proximity to the roll will cause a significant rise in ambient temperature due to convection. Thus, ambient compensation is critical in this application.

NOISE CONSIDERATIONS

"Noise is the random fluctuation of the electrical output signal (voltage, current, or power)" (Derenaiak, p.75). Noise cannot be cancelled by combining it with a signal of equal but opposite magnitude, thus it is one of the basic limiting agents on the performance of a detection system. Since noise is random it is impossible to completely eliminate it from a signal measurement. Noise from the incident radiation, the detector, and the electrical circuitry involved in amplifying and processing the signal will affect collected data to varying degrees. Types of noise include: Johnson noise, photon noise, and flicker noise.

Johnson noise, also known as thermal or Nyquist noise, is caused by the thermal motions of charged particles in a resistor. The rms power varies as a function of the temperature of the resistance and the electrical bandwidth being used.

$$P_{rms}=kT\Delta f \qquad (11)$$

where Prms=noise power in Watts; k=Boltzman's constant; T=resistor temp in Kelvin; Δf=electrical bandwidth in Hertz. The voltage of Johnson noise is V_{rms}=sqrt(4kTRΔf). Photon or quantum noise is derived from changes in the incident optical radiation. Another type of noise that consistently influences the performance of a detector is flicker noise, which appears at the frequency being evaluated. Flicker noise (pink or 1/f noise) has a power spectrum represented by $P=1/f^a$ where the exponent, a, is usually a value close to one. Many theories are available as to what causes this 1/f limitation, but the exact cause is still unknown.

In infrared devices it is vital to shield the detector from incident radiation and reduce the fluctuations seen by the detector. A cold shield, which is a 100% blackbody, can be used to eliminate this incident radiation and improve the characteristics of the bolometer. When a consistent signal, such as a DC level voltage appears, filters are one way to remove it and improve the signal-to-noise ratio. Using filters to improve a signal is particularly effective if the measured signal is a slowly changing one. A bandpass or reverse notch pass filter can reduce signal noises by removing any undesired frequency components from the signal. For the Lexmark project, filtering the signal would most likely add extra cost while not improving the signal significantly. This assumption is based on the fact that the temperature fluctuations occur quickly, and the heating lamp is not on for such a long length of time that any slow moving signal changes effect the measurements.

The current design considerations allow modifications to the detector only. Therefore any signal distortion due to amplification and processing of the signal cannot be controlled in this project. The assumption is made that if the current thermistor measurement system works sufficiently then the same electronics will be adequate for a new detector system as well. This leaves an evaluation of noise sources inherent to the detector. As much of the random incident radiation as possible should be eliminated while still obtaining a valid signal. The compensating thermistor provides much the same function that a filter would in eliminating the low frequency changes caused by the rise in ambient temperature. Some of the elctrical noise due to the wiring and circuitry of the bolometer could be reduced if the detector was operated in cryogenic conditions or had more expensive wiring. Such options were deemed unfeasible for this project since the object is to have a simple, inexpensive device.

DETECTOR DESIGN

The proposed detector design appears in Figure 8. The part is a stamped piece constructed of a suitable metal, either aluminum or steel. The material is not critical, so long as the thermal conductivity is high enough to ensure an even temperature distribution within the assembly. The aperture is sized at 2.54 mm to maximize the portion of the roll included in the field of view of the detector.

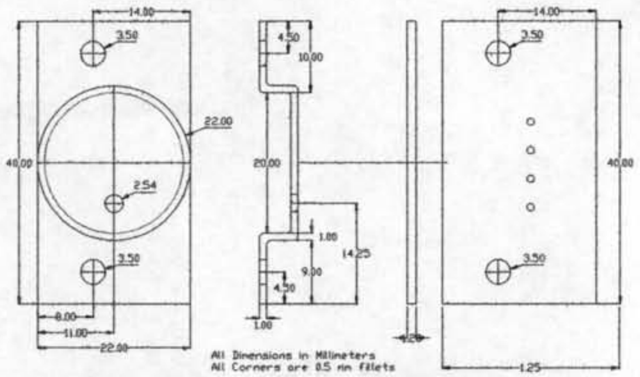

Figure 8: Proposed Design

The assembly constructed for the testing process appears in Figures 9 and 10. This test assembly was built as an alternative to the design recommended in Figure 8 due to its relative ease of construction. The aperture is the same size as in Figure 8. The bolometer is constructed from Plexiglas, and the outside surface is coated with aluminum tape with an emissivity of 0.05. The outer coating of aluminum tape minimizes the amount of radiation absorbed by the detector housing, and thus the temperature rise due to radiation. One thermistor is positioned in the aperture, the other is positioned behind the cover in direct contact with the cover. The thermistors mount rigidly to the back cover of the assembly. The assembly is made from four pieces, with three being glued together and forming the cover. The back plate is attached to the front plate and cover using screws. The two thermistors are placed along the same horizontal line. It is assumed that the thickness of the cover is small enough that the temperature gradient within the cover will be neglible, and the temperature measured at the back edge of the cover is equal to that of the front.

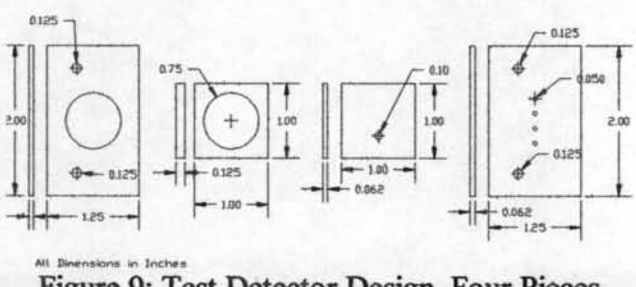

Figure 9: Test Detector Design, Four Pieces

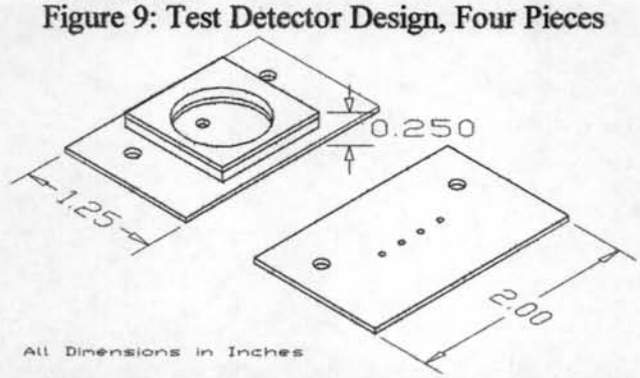

Figure 10: Completed Test Detector Assembly

The assembly is mounted to the cover assembly as shown in Figure 11. The bolometer is mounted on the end of the cover opposite from the original thermistor so the original thermistor can be retained for testing purposes. The bolometer is positioned such that it is the same distance from the outside edge as the original. It is assumed that the results from tests may be applied to a detector positioned at the opposite end of the roll because of symmetry. The design will need to be mounted at the same end as the original end for actual operation. The original is mounted such that it is at the leading edge of the paper passing through the fuser in order to detect any temperature gradient caused by the paper. It is assumed that the temperature gradient along the horizontal axis of the cylinder is negligible, both in this design and in Lexmark's design.

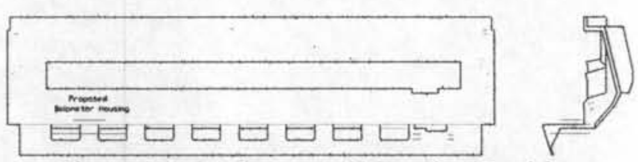

Figure 11: Bolometer Mounting Position

The aperture size was determined using the equations shown in Appendix C, which relate to Figure 12. The distances and angles indicated in Figure 12 have the following significance:

- d = distance from outside surface of hot roll to front edge of bolometer
- r_{ap} = radius of aperture
- x_{th} = distance from outside surface of hot roll to leading edge of active thermistor
- Δy = radius of thermistor
- β = angle between normal to tangent line and FOV line
- ϕ = ½ angle subtended on roll, ½ amount of roll visible to active thermistor
- θ = ½ total FOV of assembly

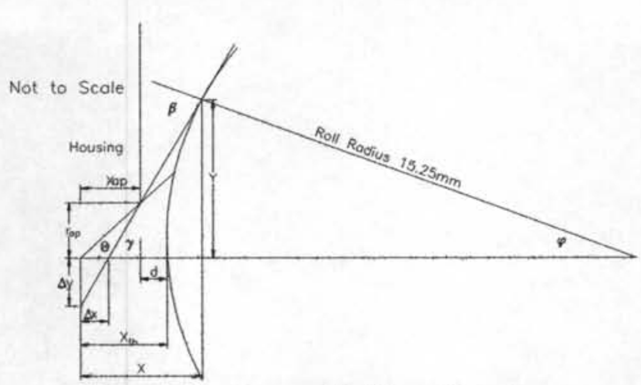

Figure 12: Geometric Considerations

The distance from the roll to the assembly was set nominally at 1.00mm, and the distance from the front of the assembly to the active thermistor was set nominally at 1.00mm. These values, along with the 2.54 mm aperature size, were used to calculate the variables represented in Figure 12. Table 1 represents the FOV, β, and ϕ for the proposed nominal distances, and also at the proposed tolerances.

Table 1: Geometric Considerations

d	X_{ap}	X_{th}	FOV	ϕ	β
1	1	2	103.56	19.09	82.70
0.75	0.75	1.5	137.02	*	99.3
1.25	1.25	2.5	80.51	11.47	64.87

It is noted that in line 2 of Table 1, ϕ does not intersect the roll. Some amount of background radiation may be seen because the FOV is not limited to the roll. Also, in each instance, β is greater than 45°. Based on the previous discussion, it is expected that much of the the radiation contributions from angles of β greater than 45° will be small.

The thermistors used in the assembly are the same as those currently used, Shibaura PSB-S3. Glass encapsulated thermistors were used to ensure stability at the high temperatures being measured. The glass will interfere somewhat with the absorption of radiation, as it will have some value for reflectivity. Assuming tempered glass, the reflection losses may be as high as 21%. To counteract this effect, the active thermistor is coated with matte black paint to increase the absorption.

Figure 13 indicates the alignment of the detector in the final assembly. The detector is positioned to be 1mm from the roll. The active thermistor is inline with the closest portion of the roll.

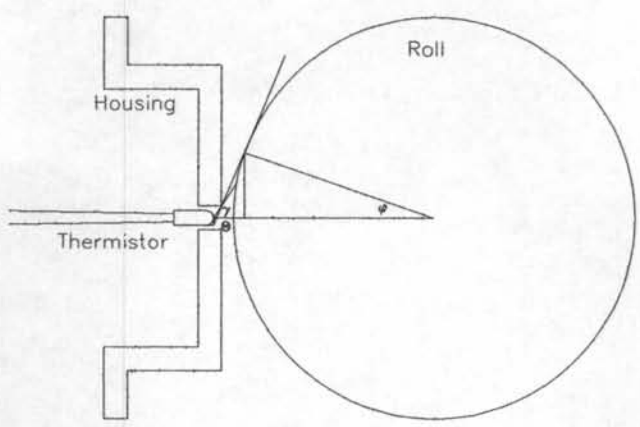

Figure 13: Final Assembly Placement

TEST PROCEDURE

From the previous discussion, it is expected that the detector assembly will still be in transient when the roll reaches its control set point due to convection. Therefore, at the control set point, the resistance of each resistor in the assembly may be any number in a range of values, as opposed to the original thermistor which has only one unique value of resistance for a given temperature. The calibration of the new assembly poses an interesting challenge. The calibration will be performed in two ways. The roll will be controlled using the original thermistor as a thermostat. The resistance of each thermistor in the bolometer will be measured independently throughout the calibration procedure. The test will be allowed to run long enough to achieve steady state conditions in the assembly. This test will be performed at both temperatures of interest, 180°C and 200°C.

In addition, the temperature will be controlled at the two temperatures, 200°C and 180°C, using a variable transformer. The lamp will receive the amount of power required to hold the roll at the control temperature, at the condition when the power into the roll equals power out through heat transfer. Once again, the response of each thermistor will be measured independently and the test will last until the assembly reaches steady state. By combining the signal from the two thermistors while the assembly is in transient, a steady value will be achieved which is indicative of the actual temperature.

The resistance was measured using an Omega WB-31 Analog/RS-232C Interface. The device measures a voltage difference between an analog input and ground. The thermistor was connected as one arm of a voltage divider. The other arm can either be the matched thermistor or a fixed resistor. Normally, thermistor bolometers are connected such that the active and shielded thermistor form the two arms of the voltage divider, as indicated earlier in Figure 6. In this instance, the output voltage will be proportional to the ratio of the resistance of the two thermsistors. In a voltage divider connected as shown in Figure 14, the resistances R_1 and R_2 are related to the output voltage according to Equation 10. The control program used during testing is in Appendix D.

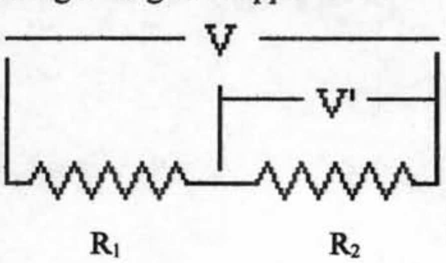

Figure 14: Voltage Divider Circuit

$$V' = \frac{V}{\frac{R_1}{R_2}+1} \tag{12}$$

When the voltage divider is connected such that the active and shielded thermistors are R_1 and R_2, the output voltage is equal to one half the total voltage when the two thermistors are at the same temperature, regardless of that temperature. This may cause problems if the operating conditions change significantly since there is no relation to the actual temperature.

Due to limitations of the WB-31, two separate computers were required. The WB-31 only has two analog inputs. One computer was used to read the original thermistor, and a separate computer was used to read the output from the two thermistors in the bolometer assembly. This produced consistency problems with the output, since the computers sampled between 1 and 2 Hz and were not always in phase.

RESULTS

The first tests of the new assembly were performed with the distances Δ and X_{ap} at 1mm each. The results were poor. The assembly was immediately modified. The distance Δ was decreased to the minimum tolerance value of 0.75 +/- 0.05mm for further testing. The distance X_{th} was decreased to 0mm. The thermistor then had a 180° field of view. This could cause problems with background radiation interfering with the active thermistor output. However, examination of the assembly and consideration of the relative position of the bolometer indicated that no sources would emit radiation that would be significant to cause error. Also, a hole of the same size as the aperature was drilled so that it vertically mirrored the aperture on the cover assembly. The shielded thermistor was moved forward so that it directly contacted the aluminum tape covering the bolometer. These new tolerances were kept for the rest of the testing process.

The original thermistor was first calibrated using the WB-31 and the thermistor connected as R_2 in a voltage divider with R_1 a fixed resistor of 1 kΩ +/- 5% (in reference to Figure 14). The output was essentially linear above 150°C. Therefore, the calibration was performed only between 150°C and 215°C. These are the only temperatures of interest, and a much better curve fit was obtained by using only these data. See Appendix E for calibration data. The results which follow will not show roll temperatures below 150°C because the thermistor was not calibrated for those temperatures.

The first test of the bolometer utilized the two thermistors, active and shielded, in the two arms of a voltage divider. The active thermistor corresponds to R_2 in Figure 14, and the shielded thermistor corresponds to R_1. The temperature was controlled using the original thermistor and a separate computer, as outlined in the Test Procedure. The results from this test appear in Figure 15.

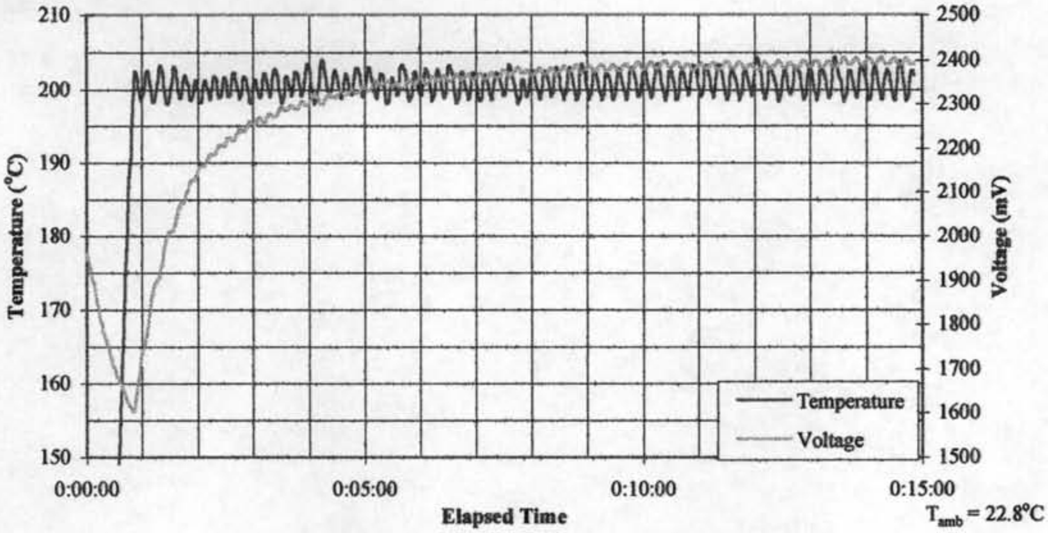

Figure 15: Bolometer Connected in Voltage Divider

The output shows no correlation to the roll temperature. When the set point is reached, the output shifts corresponding to a shift in R1/R2. The voltage divider was discarded as a way to analyze the output signal.

The test was designed to determine the temperature at which the assembly would be operating. The next test used the variable transformer to hold the roll temperature essentially constant at 200°C. The thermistors were connected in the position of R2 in two independent voltage dividers, each with a fixed resistor of 1kW +/-5% in the R1 position. Several key factors of the detector were determined from the test. The test provided some indication as to the difference in temperature between the active and shielded thermistors (Figure 16). The resistance of each thermistor was calculated using a modification of Equation (12), the known total voltage, measured voltage, and fixed resistance. This was used to calculate the temperature of the active and shielded thermistors as shown in Figure 16. The temperature of both detectors continues to rise well after the roll reaches its set point and reaches approximately 140°C. The difference in the two temperatures is extremely small, approximately 2°C. This indicates that the detector is not "seeing" much radiation.

It is apparent that the housing remains in a transient condition well beyond the roll. The voltage from the shielded thermistor continues to decrease steadily while the active thermistor responds to the temperature fluctuations of the roll.

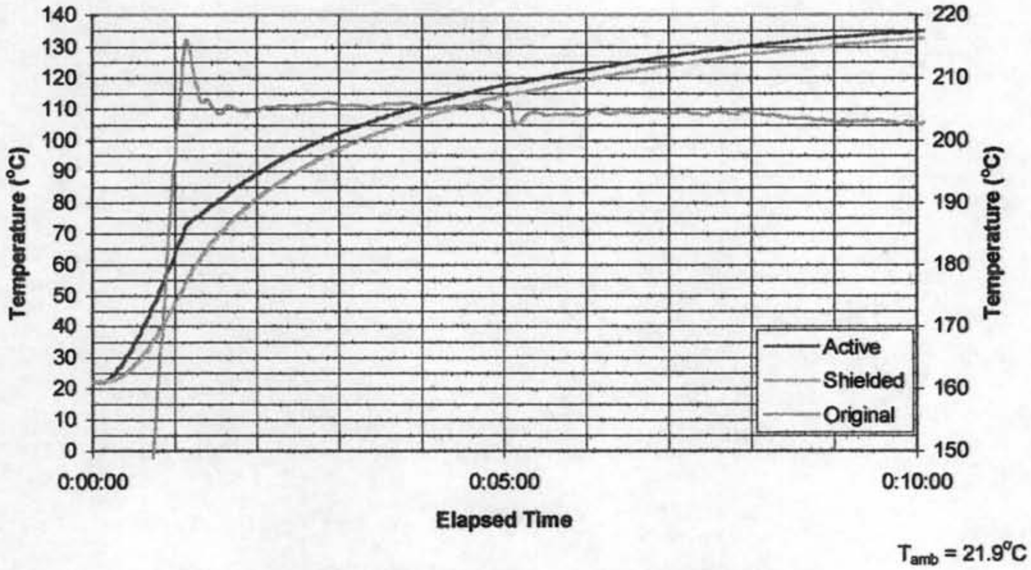

Figure 16: Temperature of Bolometer

With the operating temperature of the detector determined, a positive relation between the two output signals and the actual temperature was desired. Trying several possible combinations, it was found that the natural log of the shielded voltage to the active voltage provides the best possible correlation. This result is indicated in Figure 17. As shown in Equation (11) the natural log of this ratio is independent of source voltage provided that both thermistor are powered from the same source.

$$\ln\left(\frac{V_{sh}}{V_{ac}}\right) = \frac{\dfrac{V_{tot}}{R/R_{sh}+1}}{\dfrac{V_{tot}}{R/R_{ac}+1}} = \frac{R/R_{ac}+1}{R/R_{sh}+1} \qquad (13)$$

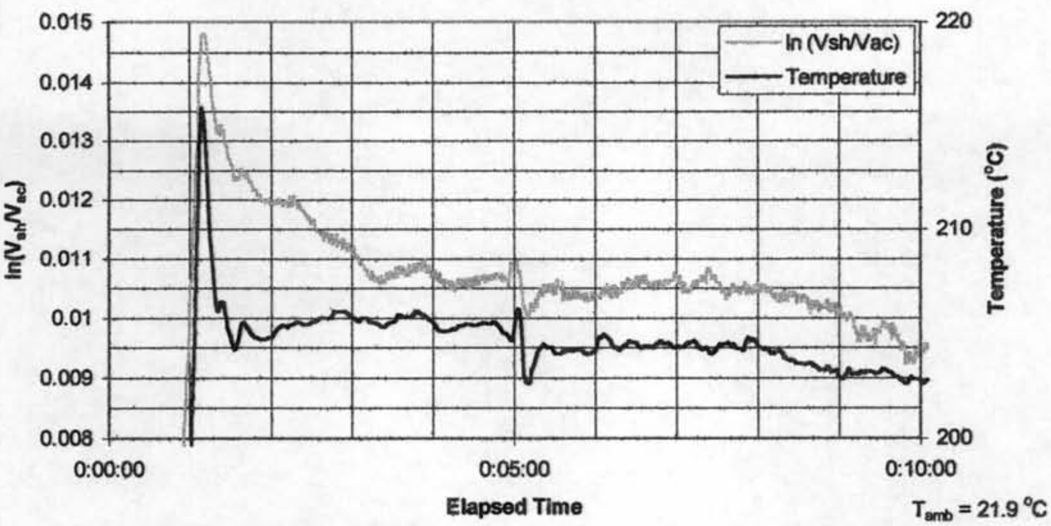

Figure 17: $\ln(V_{sh}/V_{ac})$ for Test Using Variable Transformer

Figure 17 indicates a good correlation after 3 minutes, 2 minutes after the roll reaches its set point temperature. After this, the detector signal shows a good response with the temperature and follows fluctuations in temperature. The time constant of the detector is a major concern, clearly this test indicates an impractical time constant. The convection contribution causes the assembly to respond slowly.

From the test indicated in Figure 17, and other calibration runs using both the variable transformer and original thermistor to control the temperature, it was determined that 200°C corresponds to a ln (V_{sh}/V_{ac}) value of 0.01. Based on this premise, the bolometer was used to control the temperature of the hot roll using a set point of $\ln(V_{ac}/V_{sh}) = 0.01$. The results appear in Figure 18. The long detector time constant can be seen in the figure. The roll does not reach its maximum temperature for 5 minutes. It also overshoots the desired temperature by 10°C, ending around 210°C. Figure 18 also shows the output voltage from the two thermistors, which is changing after 30 minutes. The response was improved to 5 minutes using ambient compensation.

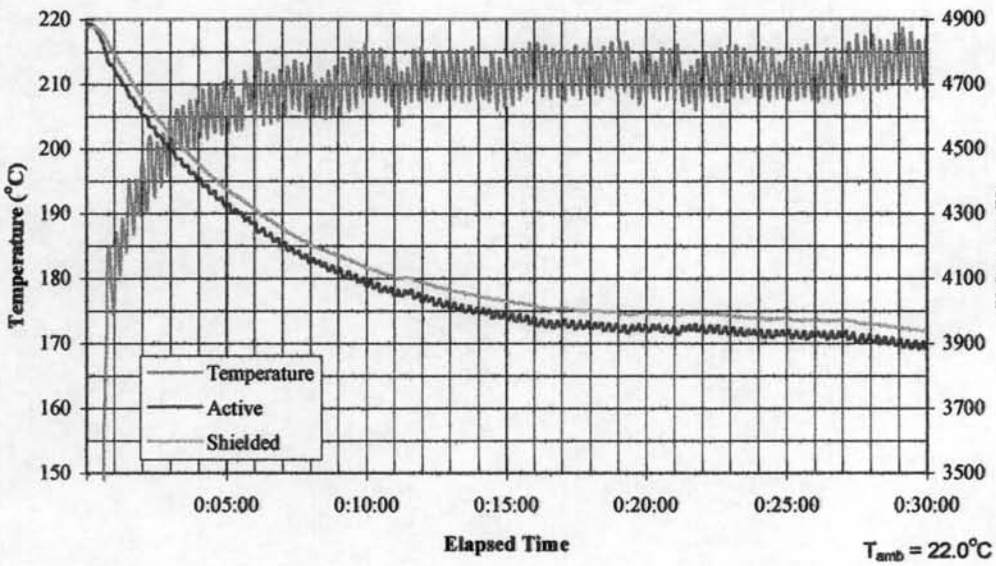

Figure 18: Bolometer Controlling at 200°C

The problem with increasing temperature can be better explained after examining the control structure of the system. Figure 19 shows the actual control signal and temperature through the test.

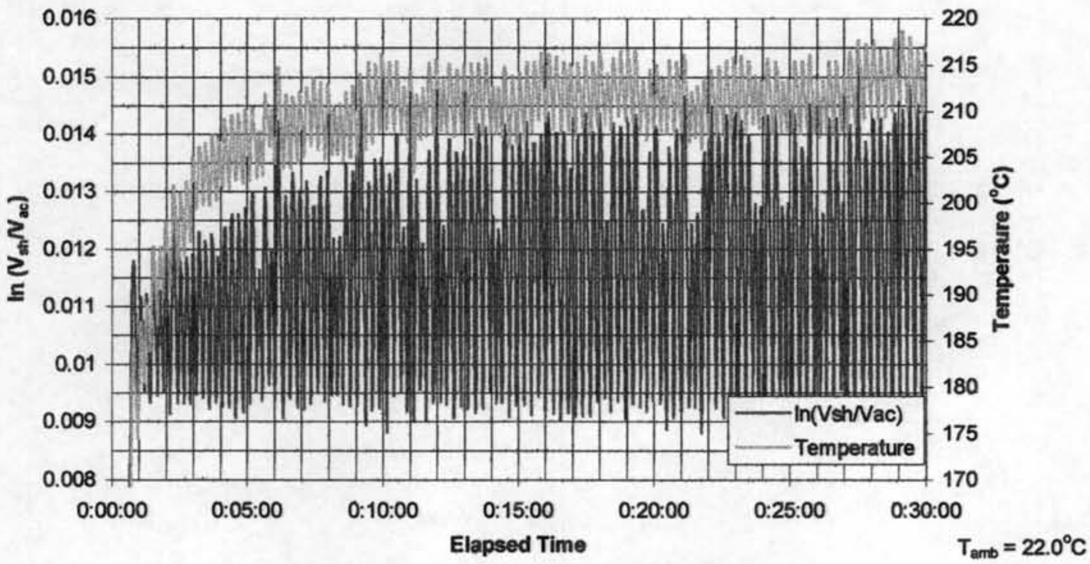

Figure 19: Bolometer Reading at 200°C

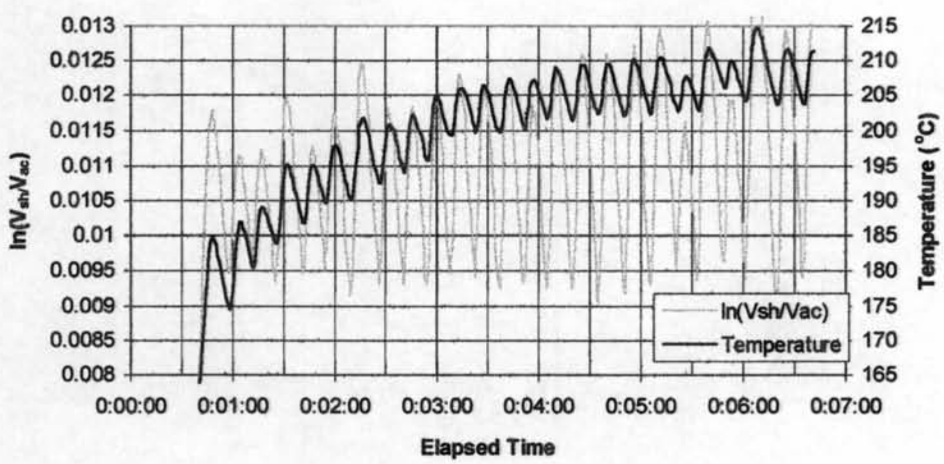

Figure 20: Control Signal

The control signal peaks increase corresponding to increases in temperature. The simple thermostat method is not sufficient. Implementing a derivative control algorithm to limit the overshoot of the $\ln(V_{sh}/V_{ac})$ signal would improve the temperature control, and the corresponding increase in roll temperature.

Additional data collected using the bolometer assembly to control the temperature at 200°C appear in Appendix E, and agree with the results indicated in Figures 18, 19, and 20.

Tests conducted with the roll held at 180°C using the original control mechanism indicated a $\ln(V_{sh}/V_{ac})$ value of 0.07 corresponded to that temperature. Using that value as the control set point yielded the results which appear in Figure 21. The same problems apparent in the 200°C test are apparent in this test, with the temperature increasing for approximately 10 minutes.

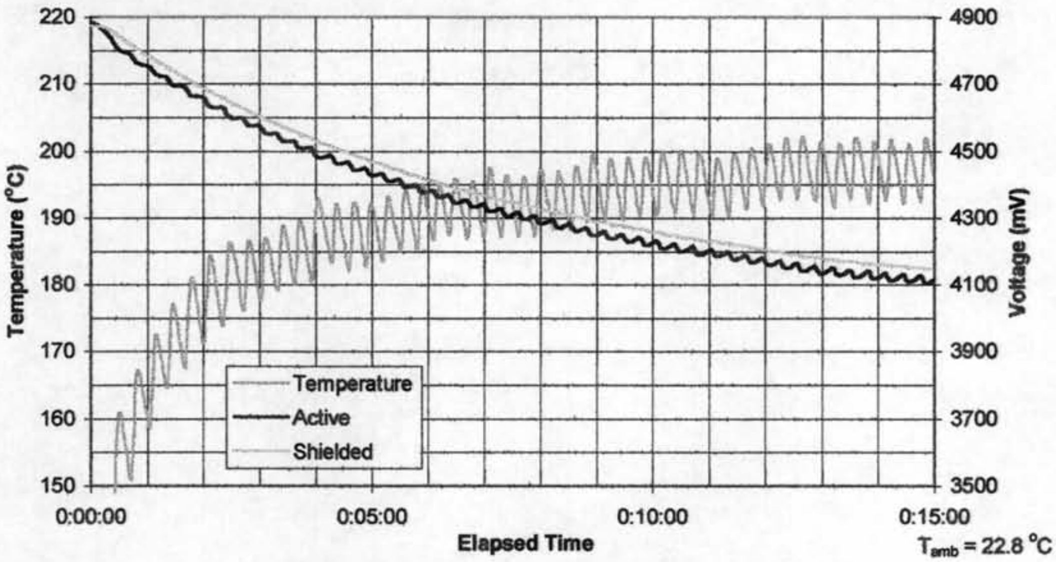

Figure 21: Bolometer Controlling at 180°C

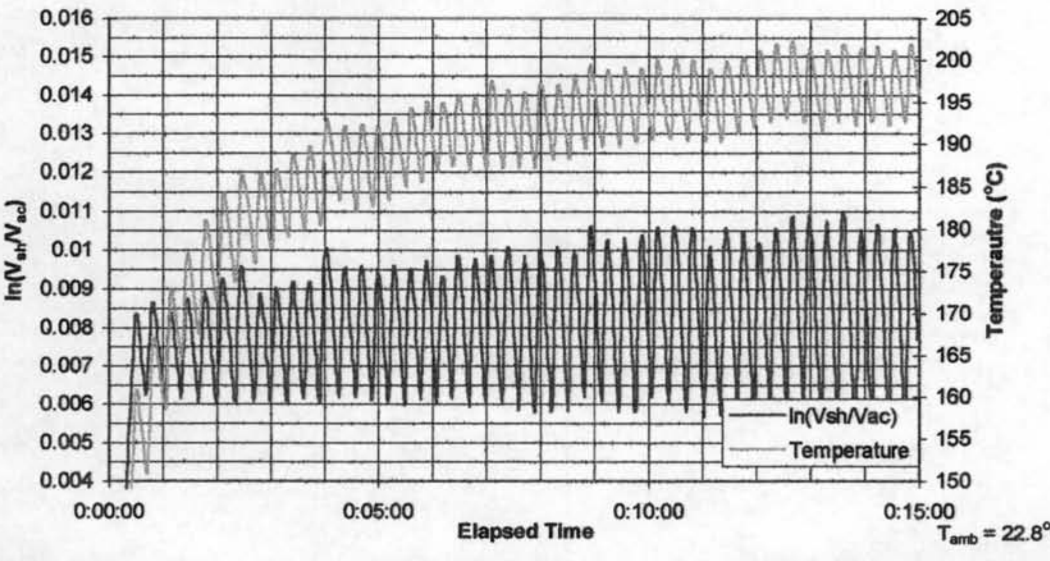

Figure 22: Bolometer Reading at 180°C

Once again, the response time of the detector is poor. The temperature stabilizes at a high temperature. The final temperature can be lowered by changing the set point from 0.07. Better control of the control signal would limit the maximum temperature achieved, but would not correct the problem with the time response.

Cooling tests performed indicated that the output from the detector shifts negative as temperature decreases. The assembly stores heat, which causes the shielded thermistor to stay at an elevated temperature. However, the assembly still reaches the correct temperature when the test is started during cooling. It would be difficult if not impossible to find achieve a temperature of 180°C when cooling from 200°C because the output would be negative at 180°C and be restored to positive values as the lamp stayed on. Analyzing the data, the difference between the resistance of the active and shielded thermistors, and hence the output voltage, is extremely small. This causes the system to be sensitive to small fluctuations in the output of either thermistors. The $\ln(V_{sh}/V_{ac})$ ratio is too small to use as a control signal, and amplification would lead to a poor signal to noise ratio.

FINAL DESIGN RECOMMENDATION

The results from testing the bolometer assembly indicate that it is inadequate to accurately control the temperature as desired. The assembly does show promise for a non-contact temperature detector. Examination of the results indicates that a suitable temperature sensor could be made by design modifications based on the original design recommendation. By forming the bolometer assembly out of a single stamped piece of aluminum the incident radiation should be reflected while the heat conduction will be increased. This increased conduction will cause the temperature measurement to stabilize more quickly. Also any variations that may occur in production of the three piece assembly would be eliminated by using a single uniform part for each fuser assembly.

Heat loss via conduction through the thermistor leads can be a significant percentage of the total heat losses, which adversely effect measurements. These losses would cause the thermistor to read a value lower than the actual value. The conduction losses would increase as temperature increases, and may account for the high final temperature. To reduce this loss the portion of the wires inside the housing should be aligned so that they are parallel with the roll.

Figure 19 (see also 24 and 26 in Appendix F) shows the bolometer readings over a period of 30 minutes. As the lamp is maintained at a certain temperature for an extended length of time, the variance about the temperature increases. As a result the temperature readings begin to become inaccurate. One possible solution to this problem could be the addition of a high pass filter to the system. The slight increases in temperature, which we believe are due to the ambient temperature increase, could be considered a very low frequency signal. By removing the slow increases the variation of the measured signal about the mean value should remain constant and acceptable.

The large mass of the detector is another problem with causing a poor response time. The large mass takes some time to reach its maximum temperature and stores heat as well. The final design proposal considers a much less massive assembly.

The assembly tested was in direct contact with the entire cover assembly. The slow response time of the detector can be also be associated with the conduction between the assembly and the fuser cover. By minimizing the conduction path between the bolometer and cover assembly, the time required for the bolometer to reach its steady state temperature would be decreased. Also, as the roll cools, the cover restores heat to the cover assembly, contributing the shielded thermistor's higher reading than the active thermistor. By isolating the assembly from the cover, the signal can be improved.

Based on these considerations, the design in Figure 23 was conceived. It acts to minimize the error sources identified in the current proposal. The part is stamped metal. The detector is less massive. The assembly is isolated from the cover assembly through four posts to reduce the conduction transfer between the cover and detector.

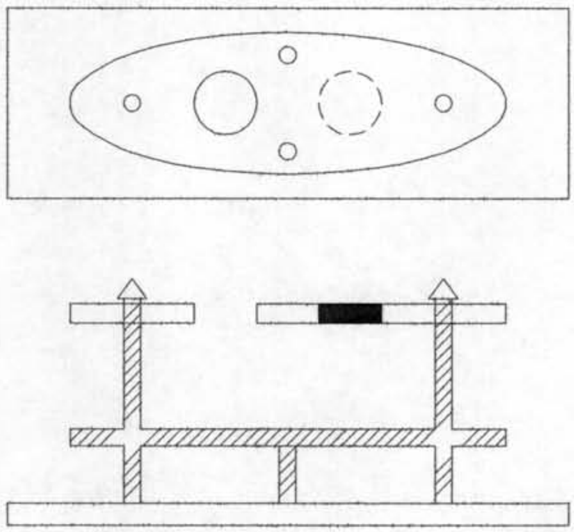

Figure 23: Final Design

The additional cost of such a detector would be small. It requires the addition of one thermistor, a simple metal assembly, and modifications to the cover assembly.

Figures 19 and 22 indicate the control signal fluctuations increase as the temperature of the detector increases. This causes a corresponding increase in the temperature fluctuations of the roll. Implementing a derivative control algorithm in order to more tightly control the control signal would decrease the temperature fluctuations about the desired set point, and is recommended with this design.

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APPENDICES

APPENDIX A: HEAT TRANSFER CALCULATIONS

I. Rate of Heat Transfer Due to Free Convection

Assumptions: neglects effects due to rotation
neglect conduction to adjacent surfaces
neglect effects of cover assembly on plume formation
assume long cylinder
assume 22.2°C ambient temperature (72°F)

Churchill and Chu's correlation, as reported by Dewitt (Dewitt, 51)

$$\overline{NU_d} = 0.53(Gr_d Pr)^{\frac{1}{4}} \qquad 10^4 < Gr_d Pr < 10^9 \qquad (14)$$

$$\overline{NU_d} = 0.13(Gr_d Pr)^{\frac{1}{3}} \qquad 10^9 < Gr_d Pr < 10^{12} \qquad (15)$$

$$Gr_d = \frac{\rho^2 g \beta (T_w - T_\infty) d^3}{\mu^2} \qquad (16)$$

$$\overline{NU_d} = \frac{\bar{h} d}{k} \qquad (17)$$

Evaluating the properties at the film temperature, $T_f = T_w + T_\infty = 384.11$ K

$\rho = 0.9105$ kg/m^3 $\qquad k_{air} = 0.0326$ W/mK
$g = 9.81$m/s^2
$\beta = 0.0026$ K-1 $\qquad T_w = 473.15$ K
$\mu = 2.23$ X 10-7 Ns/m^2 $\qquad T_\infty = 295.35$ K
Pr = 0.693

From Equations (14), (16), and (17),

$$Gr_d = \frac{(0.9105\frac{kg}{m^3})^2(9.81\frac{m}{s^2})(0.0026K^{-1})(473.15-295.35)K(0.031m)^3}{(223.1x10-7\frac{Ns}{m^2})^2}$$

$$Gr_d = 2.25x10^5$$

$$\overline{Nu}_d = 0.53(2.25x10^5(0.693))^{\frac{1}{4}} = 10.53$$

$$\bar{h} = \frac{10.53(0.0326\frac{W}{mK})}{0.031m} = 11.07\frac{W}{m^2K}$$

The total heat transfer from the roll is then found using Equation (2)

$$q = 11.07\frac{W}{m^2K}(\pi * 0.0305m * 0.2365m)(473.15 - 295.15)K = 45\ W$$

II. Heat transfer from the roll due to radiation (same assumptions as above)

Using Equation (3) and $\varepsilon = 0.92$,

$$q = 0.92(5.67x10^{-8}\frac{W}{m^2K^4})(\pi * 0.0305m * 0.2365m)((473.15K)^4 - (295.35K)^4)$$

$$q = 50\ W$$

APPENDIX B: COMMERCIAL IR DETECTOR

Model 1350 Thermistor IR Detector

For detection, measurement, analysis and control of infrared radiation

The Servo Corporation of America Model 1350 Thermistor IR detector is recommended for use in general infrared systems, pyrometers and other applications requiring broadband optical response from an uncooled detector. These devices have exceptional stability and reliability.

PERFORMANCE SPECIFICATIONS

Standard Detectors

Model 1350 thermistor IR detectors have been developed to satisfy the requirements of a broad range of applications. Active element size, resistance, time constant, and window material specify the detector. Normal tolerances are ± 10% on active element size, ± 20% on resistance (with a ± 5% resistance match between the active and compensator elements), and ± 20% on the time constant.
Please consult our applications group with your requirements for different tolerances or specifications.

Standard Configurations:

Actual Element Size: 1.0 mm x 1.0 mm, ± 10%

Nominal Element Resistance: 2.7 megohms, ± 20 %, (BTL #1 material)

Time Constant: 4. 0 milliseconds, ± 20 % (1 /e)

Responsivity: (600 K, 15 Hz): 500 volts/watt, open circuit

N.E.P.(600 K, I5 Hz, I Hz BW): 6 x 10-10 watts/cpsl/2 (less window loss)

Wavelength Response: 2 to 20 microns

Window Material (STD): Germanium

Operating Bias: Approx. 275 volts/element (specified with each unit)

Packaging: TO-8 hermetically sealed

For further information please call 516 938 9700 or email us.

APPENDIX C: DETECTOR FIELD OF VIEW

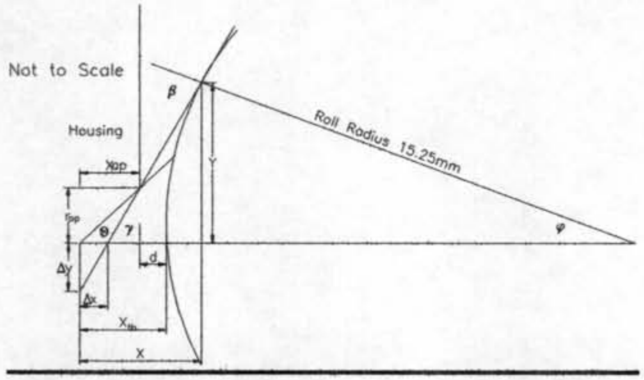

Figure 12: Geometric Considerations (Repeated)

$$\gamma = \tan^{-1}\left[\frac{\sin\phi + \frac{\Delta y}{15.25}}{1 - \cos\phi + \frac{x_{th}}{15.25}}\right] \quad (18)$$

$$r_{ap} = (x_{th} - d - \tan(90 - \gamma)\Delta y)\tan\gamma \quad (19)$$

$$\theta = \tan^{-1}\left[\frac{(x_{th} - d - \tan(90 - \gamma)\Delta y)\tan\gamma}{xth - \Delta}\right] \quad (20)$$

$$FOV = 2\theta \quad (21)$$

$$\beta = \phi + \gamma \quad (22)$$

All distances are set by tolerances

Δy = radius of thermistor

Equations (18) and (19) can be used to determine ϕ

With ϕ, use Equations (20) and (21) to find θ

Equation 21 gives the field of view

Equation 22 gives the angle β

APPENDIX D: CONTROL PROGRAM

```
DECLARE SUB DTTM ()
DECLARE SUB OPNCOM ()
DECLARE SUB HEADER (bgntme$)
DECLARE SUB RDIN ()
DECLARE SUB CLCTMP ()
DECLARE SUB OTPT (ln, y)
DECLARE SUB HEAT (h)
DECLARE SUB LEAD ()
DECLARE SUB CLSCOM ()

COMMON SHARED numtst$, tmptst,  tm, , av1, t1


CLS
PRINT "The current date is "; DATE$; " and the current time is "; TIME$
PRINT "Are these settings correct?  Type 'y' or 'n' then press <ENTER>."
INPUT dt$
IF dt$ = CHR$(78) OR dt$ = CHR$(110) THEN DTTM

CLS
PRINT "Please enter the number of this test cycle then press <ENTER>"
INPUT numtst$
PRINT "Please input the temperature for this test cycle in degrees Celsius."
INPUT tmptst

bgntme$ = TIME$


OPNCOM

HEADER bgntme$

TIMER ON
tm = TIMER

ln = CSRLIN + 1

DO
 IF TIMER >= tm + .5 THEN
  RDIN
  CLCTMP
  HEAT h
  OTPT ln, y
  tm = TIMER
 END IF
LOOP UNTIL INKEY$ = CHR$(27)

LOCATE 22, 1, 0
PRINT "The test ended at "; TIME$; " on "; DATE$; "."
PRINT #2, "The test ended at "; TIME$; " on "; DATE$; "."
CLSCOM
```

```
END

SUB CLCTMP

 t1 = -0.0397 * (av1) + 287.65

END SUB

SUB CLSCOM

 PRINT #1, "O111X"
 CLOSE #1
 CLOSE #2

END SUB

SUB DTTM
 PRINT : PRINT
 PRINT "Please enter the new date in the format mm/dd/yy and press <ENTER>."
 INPUT nwdt$
 PRINT "Enter the new time in military format and the form hh:mm:ss and press <ENTER>"
 INPUT nwtm$
 DATE$ = nwdt$
 TIME$ = nwtm$
END SUB

SUB HEADER (bgntme$)

 CLS
 PRINT "Test cycle "; numtst$; " began at "; bgntme$; " on "; DATE$; "."
 PRINT "The temperature for the test is "; tmptst; " degrees Celsius."
 l = CSRLIN + 2
 LOCATE l, 3, 0
 PRINT "Time"
 LOCATE l, 16, 0
 PRINT "Temperature"
 LOCATE (l + 1), 19, 0
 PRINT CHR$(248); "C"

 PRINT #2, "This data is for test number "; numtst$; " for which the temperature"
 PRINT #2, "is to be "; tmptst; " "; CHR$(248); "C"
 PRINT #2, "The test began at "; bgntme$; " on "; DATE$; "."
 PRINT #2,
 PRINT #2, "Time", "Temperature 1"
 PRINT #2, " ", "      "; CHR$(248); "C"

END SUB

SUB HEAT (h)

'This subroutine controls the heat lamp.  It uses a digital thermostat to
'decide the status of the heat lamp (ON/OFF).
```

```
IF t1 < (tmptst) AND h = 0 THEN
 PRINT #1, "O0XXX"
 FOR i = 1 TO 200: NEXT i
 h = 1
ELSEIF t1 > (tmptst - 2) AND h = 1 THEN
 PRINT #1, "O1XXX"
 FOR i = 1 TO 200: NEXT i
 h = 0
END IF

END SUB

SUB OPNCOM

'This subroutine opens the communications link with the WB-31 I/O device and
'sets the communications paramters. Communicate through com1, baud rate = 9600,
'7 data bits per byte, 1 stop bit, lf sends a line-feed character after a
'carraige return

OPEN "com1:9600,e,7,1,lf, cs, ds" FOR RANDOM AS #1
PRINT #1, "S01"            'set to 1 sample per record
PRINT #1, "N"              'set to 4*1mv resolution

CHDIR "c:\me479"
MKDIR numtst$
CHDIR numtst$
OPEN "test.dat" FOR OUTPUT AS #2 LEN = 2000  'file

END SUB

SUB OTPT (ln, y)

'This subroutine sends output to the screen and data file

 LOCATE ln, 1, 0
 PRINT TIME$
 LOCATE ln, 16, 0
 PRINT USING "###.##"; t1
 PRINT #2, TIME$, t1, av1

END SUB

SUB RDIN

 'This sub retrieves the input from analog channel 1 on the WB-31

 PRINT #1, "I1"
 FOR u = 1 TO 100: NEXT u
 PRINT #1, "R"
 FOR i = 1 TO 100: NEXT i
 INPUT #1, ai1$
 av1 = VAL(ai1$)

END SUB
```

APPENDIX E: THERMISTOR CALIBRATION

Actual Temperature Celsius	Output Voltage mV
150.8	3457
155.3	3338
160.6	3200
165.8	3061
170.5	2946
176.2	2772
180.9	2654
185.3	2584
190.2	2461
195.2	2328
200.3	2212
202.6	2147

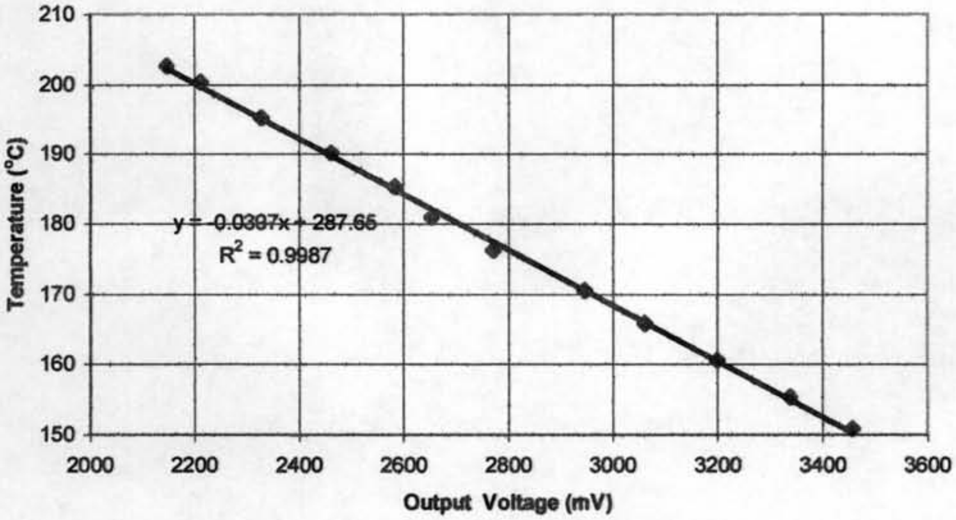

Figure 24: Thermistor Calibration

APPENDIX F: ADDITIONAL TESTS AT 200°C

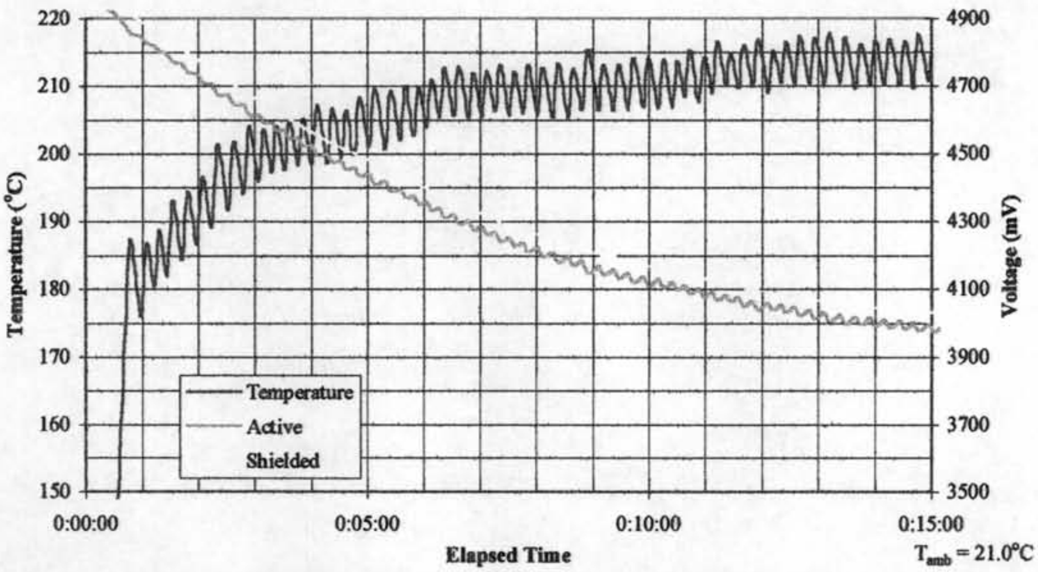

Figure 25: Bolometer Controlling at 200°C, Test 2

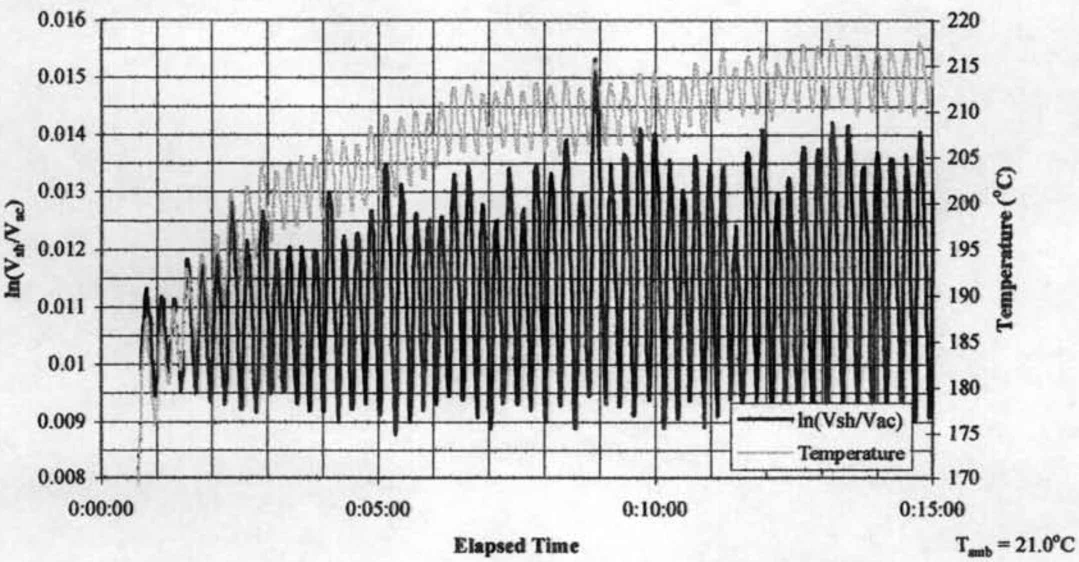

Figure 26: Bolometer Reading at 200°C, Test 2

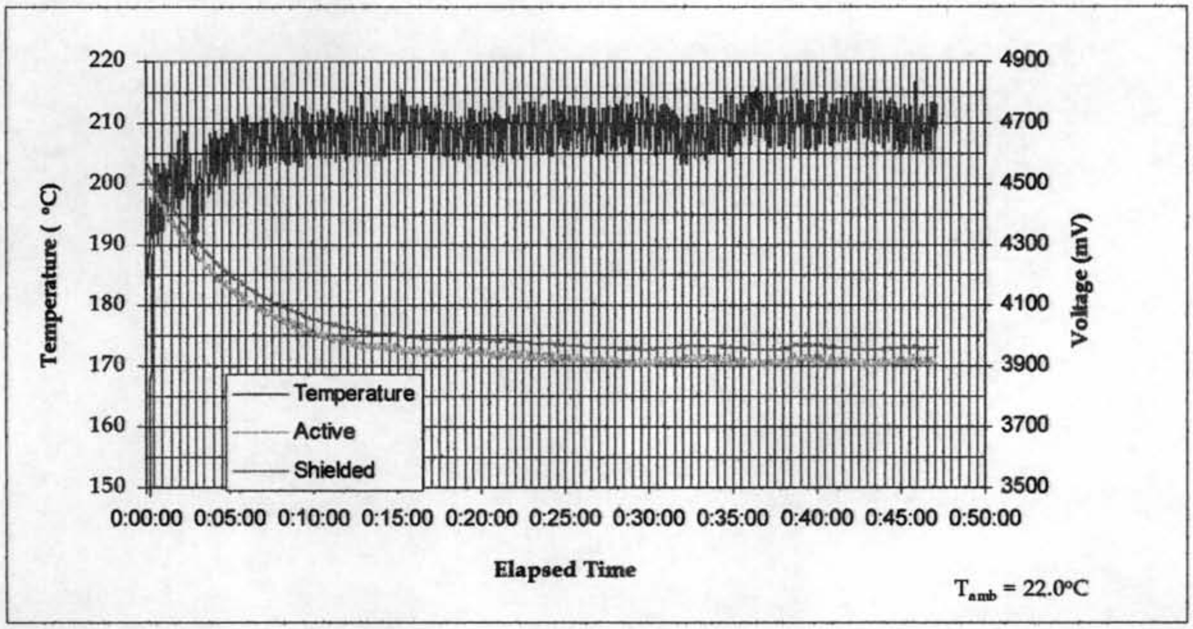

Figure 27: Bolometer Controlling at 200°C, Test 3

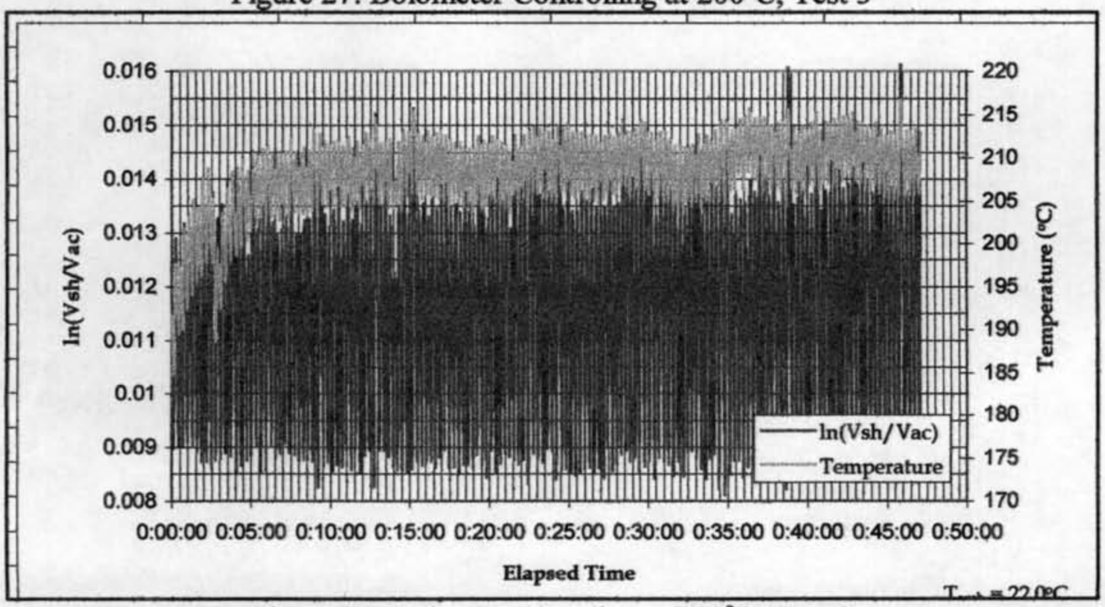

Figure 28: Bolometer Reading at 200°C, Test 3

Addendum to Lexmark Thermal Design Project

An Examination Of Non-Contact Temperature Measurement Devices

The field of remote measurement is rapidly increasing with new developments and innovations almost daily. Remote measurements can refer to sensor readings taken at a distance from the material being monitored or can involve the transmission of data from a contacting sensor to a remote data collection terminal. Noncontact methods provide a way to nondestructively evaluate the conditions of a process or material. These sensors are advantageous for a variety of fields and are based on a wide range of engineering disciplines. Applications can be found in the medical field for nonintrusive monitoring and examination of all parts of human and animal anatomy. An ultrasound of a fetus in the womb is simply a remote measurement which uses the same principles as ultrasonic detection of discontinuities on machinery welds and surfaces. Microwave sensors are used in the textile industry to monitor the moisture content of fibers. Radioactive isotopes are used to determine the density of finished fabrics and to check for corrosion of vital components such as airplane wings. Photoelectric devices are commonly found monitoring machinery speeds. The availability of this information allows operators to monitor machine and component degradation and to track product quality.

The thermal design portion of the Lexmark project required use of a noncontact sensor to monitor the temperature of the fuser roll assembly. The goal of the sensor change was to improve product quality and life of the roll assembly for a minimal cost and degree of modification to the assembly itself. This portion of the paper will explore methods of noncontact temperature measurement which were not applicable for the Lexmark design. In most cases, these designs were rejected based on cost of implementation due to the cost of the components involved. Many commercially available sensors were not appropriate because of their excessive size. Some sensors were limited by the size of the accessories needed to utilize them in the ambient temperature range of the roll assembly. As seen in the final design considerations of the project, the roll assembly housing could be modified to accommodate a slightly larger temperature sensor but the cost incurred with such modifications restricted the type and extent of the changes.

Most noncontact methods of temperature measurement are based on measuring the radiation emitted by the object of interest. The range of the electromagnetic spectrum in which thermal radiation occurs is between 0.1 and 100 micrometers, with shorter wavelengths indicating higher temperatures. Emitted radiation is related to temperature to the fourth power with constants and corrections used dependent on the materials involved. Various types of radiation detectors are utilized for temperature measurement each with particular advantages. Some of the detectors are similar to standard contact temperature measurement devices with the addition of optics or special circuit compensation. All radiation detectors must have a method for modifying the emissivity value if they are to be used for more than one material or temperature.

Infrared

Many of the radiation temperature detectors in use measure the infrared portion of the spectrum. Infrared wavelengths coincide with thermal radiation varying from 0.7 (just after visible light) to 100 micrometers.[1] The infrared portion of the spectrum then continues to 1000 micrometers. Infrared thermometers generally detect radiation less than 20 micrometers in length because that range is least affected by atmospheric conditions.[2]

Infrared sensors are simple to install and operate and have been in use for many decades. Consequently infrared detectors are available in a wide variety of options to suit the application. The specifications for the input range and output are two of the most important features for determining whether a sensor is suited for the required use. The Thermalert line of infrared temperature sensors together cover the range of -18 to 2000 degrees C. Each sensor generally can monitor a 200 to 700 degrees C range[3]. Unless these sensors have some type of cooled housing they cannot typically operate in ambient temperatures much beyond room temperature. The ambient temperature was a consideration in choosing a sensor for the Lexmark design since the assembly could remain at 180 degrees C indefinitely while the printer is in use. Air cooled and water cooled housing made the sensors much too large to fit in the allotted space in the printer; one water cooled housing almost tripled the size of a sensor.[4] Output from infrared sensors is generally either a 4-20mA current or a thermocouple output. These output types are based on industry standards and general acceptance.

Thermopiles and Thermistors

A thermopile detector is a thermocouple circuit with multiple junctions which produces thermoelectric power. Generally it is used in the same temperature measuring capacity as a thermocouple but producing an amplified voltage signal. The larger signal increases the signal to noise ratio which could pose a problem for a single thermocouple.

Thermistor sensors are based on the relationship that resistance is equal to resistivity of a material multiplied by its length and divided by its cross sectional area. Since resistivity is a function of a material which varies at different temperatures then resistance will also vary with temperature. The relationship is

$$R=R_o e^{\beta(1/T-1/To)}$$

where β varies for every thermistor based on material, construction, and temperature.[5] Therefore the thermistor will decrease in resistance with accompanying temperature increases. The Lexmark design was based on a thermistor radiation sensor due to the small size and cost.

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[1] Figliola, p363.

[2] Infrared FAQ.

[3] Thermalert TX.

[4] Strandberg Engineering Laboratories, Inc.

[5] Figliola, p337.

Eddy Current

Eddy currents used as temperature sensors function in a manner similar to thermistors. They are based on a known relationship between temperature and the resistivity of a material. Eddy currents are used on aluminum sheets exiting hot-finishing mills. The aluminum acts as the resistor in the circuit replacing a thermistor. Pairs of coils can be mounted almost one meter away from the material to be measured. The temperature can be calculated with this method despite the lubricant bubbles present on the aluminum and the rapid speed of the metal as it is rolled. An accuracy of +/-7 degrees C can be achieved if the eddy current method is calibrated with a thermocouple prior to the hot rolling. This calibration corrects for changes in composition of the material.[6]

Pyrometer Ellipsometer

Pyrometers measure radiation on a plane and ellipsometers measure the physical properties of thin films. Together they create a technique which offers accurate temperature measurement with no assumptions. This process also determines the surface refractive index and extinction coefficient.[7] When taking measurements it may be necessary to reduce the amount of direct radiation by using appropriate filters in conjunction with the pyrometer. In this manner, only the diffuse radiation of interest will be measured. Pyrometers are generally portable, handheld temperature measurement devices. Ellipsometers are more commonly used for in situ monitoring of semiconductor thin film fabrication.

Acoustic Tomography

A current study is using acoustic tomography to visualize three dimensional temperature variations. Primarily used for large oceanic wave studies tomography uses ultrasonic waves between sensors to determine movement and properties of the water. Temperature distribution is determined based of the phase differences between pairs of sensors. The results thus far correlate significantly with thermocouple readings. These findings indicate that acoustic tomography may be a good temperature assessment for large bodies of fluid.[8]

The prices for the commercially available sensors in this study were a minimum of $200 without any of the options or accessories, such as a cooling unit. This value does not account for volume purchasing or special "stream-lined" models. It is possible however to build an effective noncontact temperature sensor for a minimal amount. The bolometer that was built for the Lexmark design, including some of the modification needed for the housing, cost less than $10 per unit. The other sensors discussed, the eddy current and acoustic tomography, were found as specialized studies and as such are assumed to be quite costly.

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[6] Eddy Current Thermometer for Aluminum Processing.

[7] Hauge.

[8] Zhu.

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Non-Contact Temperature Measurement of a Printer Fuser Assembly

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The sponsor company, Lexmark, wanted to examine the possibility of a non-contact method of measuring the temperature of the hot roller fuser assembly in their low end laser printer. The current method involves a thermistor mounted on a thin film which contacts the roller. This contact leads to premature wear of the roller and the buildup of impurities under the film. By finding a way to make the measurement remotely, the life of the roller could be extended such that it would match the life of the printer; thus eliminating three changes of the roller assembly.

The primary limitations in the design were size, effectiveness, and cost. This eliminated such choices as fiber optics and photoconductive infrared detectors. The design should be as small as possible and require few modifications to the current cover and assembly. Effectiveness is determined by the following: The measurement design should be ablr to control the fuser assembly lamp such that the aluminum roller can be held at a nominal temperature +/- 5. The final design of a thermistor based bolometer was chosen. A bolometer is a configuration of two thermistors connected in a bridge circuit. One thermistor is Active and the other is the shielded or "compensating" thermistor. This shielded thermistor accounts for changes in the ambient temperature as the roller assembly is in use.

At this point it appears that the bolometer will produce acceptable results. By manipulating the data after collection we were able to obtain a reasonable degree of certainty regarding the temperature reading. The data manipulation consists of taking the log of the ratios of the resistances from the two thermistor. Currently we are trying to find a circuit that will perform this transformation in the hardware, rather than the software, to ease the implementation of the design into production.