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An Investigation of Infrared Thermography Used in Predictive Maintenance Programs to Detect Electrical Motor Failure

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An Investigation of Infrared Thermography Used in Predictive Maintenance Programs to Detect Electrical Motor Failure

AN INVESTIGATION OF INFRARED THERMOGRAPHY

USED IN PREDICTIVE MAINTENANCE PROGRAMS

TO DETECT ELECTRICAL MOTOR FAILURE

A Research Paper for Presentation

to the Graduate Faculty of the

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In Partial Fulfillment of the

Requirements for the Non-Thesis

Master of Arts Degree

by

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CHAPTER I

INTRODUCTION

In the electrical maintenance field one component that sees a lot of stresses both electrically and mechanically are electrical induction motors. Most maintenance programs that have either predictive or preventative monitoring of motors use vibration analysis methods. To be effective, programs need more that one method of monitoring electrical motors. Since the 1970's there has been an increase in Infrared Thermography applications in the electrical maintenance field.

Statement of the Problem

The problem of this study was to investigate if Infrared Thermograph Techniques could be used in detecting and predicting electrical motor failures.

Statement of Purpose

The purpose of this study was to investigate the possible use of infrared thermography as a method to monitor and predict electrical motor failures. A secondary purpose was to investigate if electrical motor components such as bearings, motor windings, and rotors were visually detectable thru infrared thermography.

Statement of Need

The need for this study was based on a need to find other means to monitor and predict electrical motor failures. The brief review of the literature investigated the use of Infrared Thermography in predictive electrical maintenance programs. The literature also investigated if these techniques could be used to specifically predict electrical motor failures.

Predictive Maintenance Tools

Keeping machinery and equipment operating properly is critical in industry. A maintenance department's prime objective should be to prevent equipment failure and consequent production loss (Renwick & Babson, 1985, p. 324). In some industries only emergency maintenance is practiced. Under this program machines are only repaired after a piece of equipment fails. Other maintenance programs have estimated the cost of routine testing and repair over a period time. This type of program has been referred to as preventative maintenance (Halfen, 1985, p. 111). A new method that is increasing in use is called predictive maintenance. These programs use various measurement techniques to indicate incipient problems, and plan appropriate maintenance to prevent failures in equipment (Halfen, 1985, p. 112).

Most cost saving comparisons are estimated against the cost of lost production (Halfen, 1985, p. 111). One rule of thumb that has been professed is that predictive maintenance programs result in an average savings of 20 percent of direct maintenance costs plus twice that in increased production (Nolden, 1987, p. 38).

Predictive maintenance is not the only solution for all maintenance problems. No single technique or system will resolve all of the requirements for a total predictive maintenance program (Mobley, 1989, p. 56).

Some major benefits that can be gained from a predictive maintenance program include reducing equipment and production downtime, reducing periodical out of service repairs, improving product quality, eliminating unnecessary repairs, and increasing production efficiency (Mobley, 1989, p. 54).

There is no single monitoring technique that can fill the needs of all critical machinery, equipment, or process lines in a typical plant. Therefore predictive maintenance programs use a number of techniques to monitor equipment while they are running. The most prevalent methods used have been vibration analysis, operating dynamics, visual inspection, infrared thermography, process parameter analysis, wear particle analysis, ultrasonic inspection, spectrum analysis, surge testing, and shock pulse testing (Mobley, 1989, p. 56; Nolden, 1987, p. 42-43; Reis, 1989,

p. 93; LeFevre, 1987, p. 103; Halfen, 1985, p. 112).

Since not all these methods are usable when equipment is in operation it is very important that a predictive maintenance program have the ability to identify and measure critical variables through several different techniques (Halfen, 1985, p. 112). Some of these techniques enable plants to monitor equipment while it is running, predict when a failure will occur, and schedule corrective repairs before the actual failure occurs (Katzel, 1987, p. 62).

Electrical Motor Failure

One component that is essential to the function of manufacturing and process plants is the electric motor (Schump, 1989, p. 386). Many large plants have thousands of different sizes and types of motors that are critical to production and safety (Nialen, 1989, p. 391; Schump, 1989, p. 386). In most maintenance programs it is standard practice to simply run motors until they fail. In other maintenance programs periodic visual inspection and lubrication, have been the limit of maintenance practice. Generally the cost of motor failure is measured by the loss of plant output or production and this cost far exceeds the cost to replace the failed component (Sottile & Kohler, 1989, p. 992; Schump, 1989, p.386).

Electric motors can fail both mechanically and electrically. Mechanical failures are primarily motor bearing failures and are attributed to mechanical factors, such as shaft misalignment, vibration, lubrication breakdown, or magnetically induced currents between the rotor and stator. These factors can cause excessive heating in the outer bearing race. This heat in turn destroys the lubrication and ultimately destroys the bearing causing motor failure (Walker, 1990, p. 90-92).

Electrical failures in motors are usually attributed to either electrical insulation failures or rotor failures (Bonnett & Soukup, 1986, p. 1165-1167; Kerszenbaum & Landy, 1984, p. 1854; Schump, 1989, p. 386-390). Insulation failure can occur between the copper windings and the stators steel core. The insulation material available today is extremely durable and usually only fails at high temperatures or under chemical attack. The major electrical insulation failure is in the thin film of polymer applied to the surface of the copper wires that make up the motor windings. The magnetic forces that turn the motor also cause motion in these windings, this in turn causes wear between the wires and abrades the insulation, leading to shorting and arching in the windings. Heat generated in motor start-ups and operation also deteriorate winding insulation. A 10 degree temperature rise will cut insulation life in half (Schump, 1989, p. 386).

Rotor failure is another major cause of electrical motor failures. The rotor is the secondary winding in the motor and is not connected to the electrical power supply. The rotor obtains its power from inductive flux produced by the stator windings (Bonnett & Soukup, 1986, p. 1165).

Thermal stresses and overloading are the major cause of rotor failures. Thermal overloading can occur during acceleration, excessive starting, normal running, or stall conditions. Thermal stresses can occur due to rotor rubbing, insufficient ventilation, unbalanced phase voltages, alignment, material defects and broken rotor bars (Bonnett & Soukup, 1986, p. 1167).

Broken rotor bars create temperature gradients due to unequal circulating currents and electrical sparking between the rotor and stator, both of which cause premature motor failures (Bonnett & Soukup, 1986, p. 1167; Kerszenbaum & Landy, 1984, p. 1858). In a study of power plant motor failures, broken rotor bars accounted for 5% of all failed motors (White, 1988, p. 55).

Infrared Thermography Used In Predictive Maintenance

Infrared (IR) thermography has become an effective tool in preventative and predictive maintenance programs (Feit, 1988, p. 54; Baur, 1986, p. 9). It has proven to be a particularly effective technique for locating electrical problems in equipment and machinery in industrial applications due to the fact that failures are proceeded by changes in operating temperature (Grover, 1990, p. 142; Feit, 1990, p. 26).

Early IR equipment was bulky, unsophisticated, and expensive, requiring the use of liquid nitrogen (Dawson, 1990, p. 82; Grover, 1990, p. 141-142). Todays equipment is more portable, does not use liquid nitrogen, and has dropped in price. The equipment is capable of detecting surface temperature differences as small as 0.1 degree C over a range of -20 degree C to 2000 degree C. Todays IR scanners can detect rapid changes in operating temperatures, making them a new tool for many applications (Feit, 1988, p. 60; Dunn, 1986, p.45).

There are three basic types of IR scanners available thermometers, line scanners, and thermal imagers. Thermometers sample and measure radiation over a wide spectrum band on small surface areas and determine actual temperatures for digital and analog outputs. Line scanners are used to locate different temperature gradients along a line of sight. Thermal imagers scan an entire surface of an object and convert narrow bands of radiation to a visual display of contrasting intensities viewable on various types of visual and storage devices (Baur, 1986, p. 9).

Permanent records called thermograms can be produced by attaching a camera to the equipment, but the latest digital imagers use electronic and computer interfacing which enable mapping of actual surface temperature distributions and recording information for storage and analysis (Baur, 1986, p. 9; Grover, 1990, p. 142; Logan, 1985, p. 191). This gives IR thermal imagers more accuracy in multiple target aquisitions and temperature profile interpretations than other devices, making it an effective predictive maintenance tool (Dresser, 1989, p. 86).

IR scanning has the advantage of being a non destructive method that permits viewing equipment from a safe distance and readings can be taken quickly and easily. IR scanning also has the advantage of being taken during normal equipment operation and load conditions while providing faster and more accurate readings than thermocouples or other measuring techniques (Grover, 1990, p. 142; Dawson 1990, p. 82; Cielo, Maldague, Deom, & Lewak, 1987, p. 452).

The most common application of IR thermography used in predictive maintenance programs has been in electrical maintenance systems. Most of these applications have focused on corroded or loose connection and conductor overloads, substation monitoring, motor control centers, motor starter operations, and power distribution equipment operations (Grover, 1990, p. 142; Baur, 1986, p. 10).

Summary of Need

Research of the literature indicated that Infrared thermography has and is being used as an effective tool in predictive maintenance programs especially in electrical applications (Baur, 1986, p. 10; Feit, 1988, p. 54). Electric motors are one major component in industry and their failures are traceable thru increases in heat generation prior to failure (Schump, 1989, p. 390; Walker, 1990, p. 90-92). Infrared imagers have shown that bearing failures in electric motors are detectable with the accurate and sensitive scanners that are available today (Feit, 1986, p. 90).

Although Infrared thermography techniques and equipment can detect electromagnetic fields that produce heat in electrical equipment (Grover, 1990, p. 142) specific application of electric motors have not been indicated in the literature as a method to predict electrical motor failure. Studies using infrared thermograph equipment on electric motors needs to be researched further to determine its use as a predictive maintenance tool.

Questions to be Answered

The following questions were to be answered in this investigation:

1. Are Infrared scanners capable of sensing a change in surface heat created by the rotor, bearings, or stator windings in all electric induction motors?

2. Are Infrared thermography techniques an effective method that can be implemented in predictive maintenance programs?

Assumptions

The following assumptions were made in this investigation:

1. The first assumption was that there was a need to use more than one monitoring method in predictive maintenance programs.
2. The second assumption was that the internal components that fail in an electric motor will generate sufficient heat to be detectable.
3. The third assumption was that electric motors will be available and in use over a long period of time to observe.

Limitations

The following limitations are inherent when using Infrared thermography equipment and were some of the baring factors that prevented descriptive or experimental testing:

1. To properly analyze the visual scans a person needs special training to use the device (Roberts, 1983, p. 54-55).

2. Todays equipment costs from $12,000 to $70,000 limiting the availability for use (Grover, 1990, p. 142).
3. Only surface measurements in the direct line of sight can be measured (Roberts, 1983, p. 54-55).
4. Shiny surfaces reflect thermal radiation from other sources which can result in erroneous temperatures although training can reduce this limitation (Roberts, 1983, p. 54-55).

Definition of Terms

The following definitions were taken from the Electronics Learning Dictionary by Rudolf F. Graf, 1977.

Induction motors - Are AC motors in which the primary winding (usually the stator) is connected to the power source and induces a current into a polyphase secondary winding (usually the rotor).

Infrared - Radiations emitted by a hot body, with wavelengths just beyond the red end of the visible spectrum. These wavelengths are longer than those of visible light and shorter than those of radio waves.

Thermography - The process of recording the distribution of temperature over the surface of an object by detecting the heat radiation from it.

Bearings - Support for a rotating shaft. In electric motors bearings fit over the rotor shaft and are retained in the motor housings.

Windings - A conductive path, usually wire, inductively coupled to a magnetic core or cell.

Rotor - The rotating member of an electric motor.

Stator - The nonrotating part of the magnetic structure in an induction motor. It usually contains the primary winding.

Rotor bars - A conducting bars that are a part of the rotor design and are separated by insulating material.

(Bonnett, A. & Soukup, G. 1988)

CHAPTER II

METHODOLOGY

This paper was an investigation into the possible use of infrared thermography as a method to monitor and predict electrical motor failures. Due to the high cost of purchasing a thermal imaging system an experimental methodology could not be performed. The methodology followed was a literature search of books, journals, magazines, and commercial manufacturing literature. The subject topics researched were infrared history, infrared thermography, predictive and preventative maintenance programs, and electrical motors failure.

In addition James Griffin an AGEMA engineering sales representative, came to the John Deere Engine facility and demonstrated the Thermovision 470 System by AGEMA. In this demonstration a thermograph of an electrical motor drive was recorded, due to technical difficulties and lack of time, a recording of an electrical motor thermograph was not accomplished. A video tape was given to the maintenance department that does show how this system can monitor electrical motor temperatures.

Further information of the AGEMA 470 system was gained in a telephone discussion with Brian Schonavic, a service technician for the James Griffin company, on the design and technical function of the AGEMA system.

CHAPTER III

HISTORICAL AND TECHNICAL INFORMATION

The electromagnetic spectrum is an arrangement of radiation according to wavelength, frequency, or photon energy. This spectrum includes wave lengths from a fraction of a millimeter to many kilometers. There has been no single detection mechanism that can be used for the entire electromagnetic spectrum. The electromagnetic spectrum has been subdivided into spectral regions based on the various means of generating, isolating, and detecting radiations (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 1).

All electromagnetic radiation when absorbed by matter produces heat. The spectral region known as the **Infrared (IR)** region is more readily detected by the heat it produces. The infrared region is generally defined by the wavelengths lying between the visible and microwave regions of the electromagnetic spectrum. The IR region has been further subdivided into near, intermediate, and far distances from the visible region (Avram & MaTeescu, 1966, p. 22; Kruse, McGlauchlin, & Mc Quistan, 1962, p. 1; Wright, 1973, p. 1).

From a quantitative standpoint infrared radiation is defined most often by the wavelengths between 7.5×10^{-4} mm and approximately 1 mm. Which is found written in texts as $0.75\ \mu$m(microns) to $10^3\ \mu$m. The frequency range of the infrared region is recognized as 3 X 10^{11} HZ (hertz) to 4 X 10^{14} HZ. When referring to photon energy the infrared region is defined between 1.23 X 10^{-3} EV (electron volts) to 1.72 EV. When referring to wave numbers 10cm-1 to 1.3 X 104cm-1 (# of waves per cm) is used. All of the measurements define a region between the visible region and the microwave region within the electromagnetic spectrum, although most of the time the micron (μ) or wave length designation is used as seen in figure 1 (Avram & MaTeescu, 1966, p. 22; Kruse, McGlauchlin, & Mc Quistan, 1962, p. 1; Wright, 1973, p. 1).

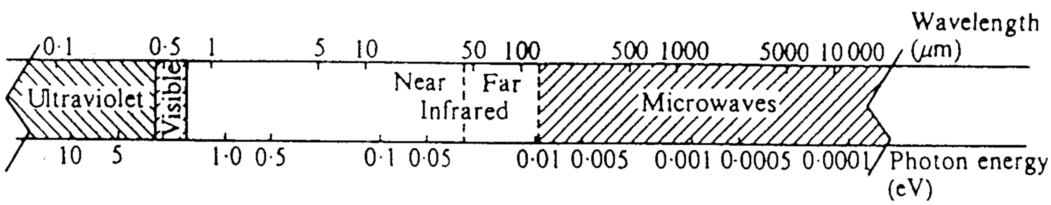


Figure 1 — Position of infrared in the electromagnetic spectrum.

Source: Infrared Techniques (p. 1) by C. H. Wright, 1973, Oxford: Clarendon Press. Copyright 1973 by Clarendon Press. Adapted by permission.

As stated by Spiro, "Every object in the Universe is constantly emitting and receiving Infrared radiation from every other object, depending on its temperature, emittance, and absorptance of its surfaces" (Spiro & Schlessinger, 1989, p. 53). The fact that every object emits, absorbs, transmits, and reflects infrared radiation in a characteristic manner has led to a long history of trying to measure and detect infrared radiation. With the technological advances in the semiconductor and computer technology of today, infrared detectors are finding increased application in not just military and scientific applications, but also in medical, industrial, and civil uses. The systems produced today create visual images and pictures which can be easily digitized, stored, interpreted, and analyzed quantitatively.

<u>Discovery of the Infrared Spectrum</u>

The discovery of the infrared spectrum by Sir William Herschel in 1800 was influenced and preceeded by many scientists studying optics. As far back as 4 BC - 64 AD Seneca discussed various topics related to optics and refraction. Further study on optics were done between 965-1038 AD by the Arabian scientist Alhayen. It was thru the works of Galileo Galilei between 1564-1642 that the true science of optics was founded. Willebrord Snell added understanding with his discovery of the Law of Refraction for optics between 1591-1626 (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 2).

The next major figure in the scientific world was Sir Isaic Newtons studies in optics between 1642-1727 leading him to be considered the founder of spectroscopy. Prior to Newtons experiments in 1666 it was believed that the visible spectrum resulted from a mixture of light and darkness. By Newton using a prism the spectrum of different light colors were separated and recombined to white with a second prism.

Newtons experiments led him to explain that all colors have the same origin as the colors arising from interference effects in thin films and that light particles travel faster in a dense medium because they are attracted to its surface (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 3). Although these explanations were incorrect they stood until 1850 when Foucault showed that the velocity of light was less in a denser medium and refraction based on the wave theory of light by Hygens 1629-1695 was correct (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 3).

During the 1700's there was little changes in the sciences of optics and spectroscopy. It was not until 1800 that Sir William Herschel discovered the infrared spectrum and the first infrared detector, the thermometer.

Herschel was born in 1738 in Hannover Prussia. He made his living as a professional musician. In 1773 he became interested in astronomy, he began to make his own mirrors for his telescopes due to the poor optical quality and high costs of commercial mirrors. In 1780 while using one of his own telescopes he discovered Uranus, earning him an appointment as Royal Astronomer to King George (Hudson & Hudson, 1975, p. 2; Wright, 1973, p. 2).

In an attempt to find a better filter to protect his eyes while observing the sun, Herschel discovered the infrared spectrum. Herschel constructed a monochromator consisting of a prism mounted in a window shade projecting the light spectrum on a table. Figure 2 shows Herschels projection of visible and infrared spectrums.

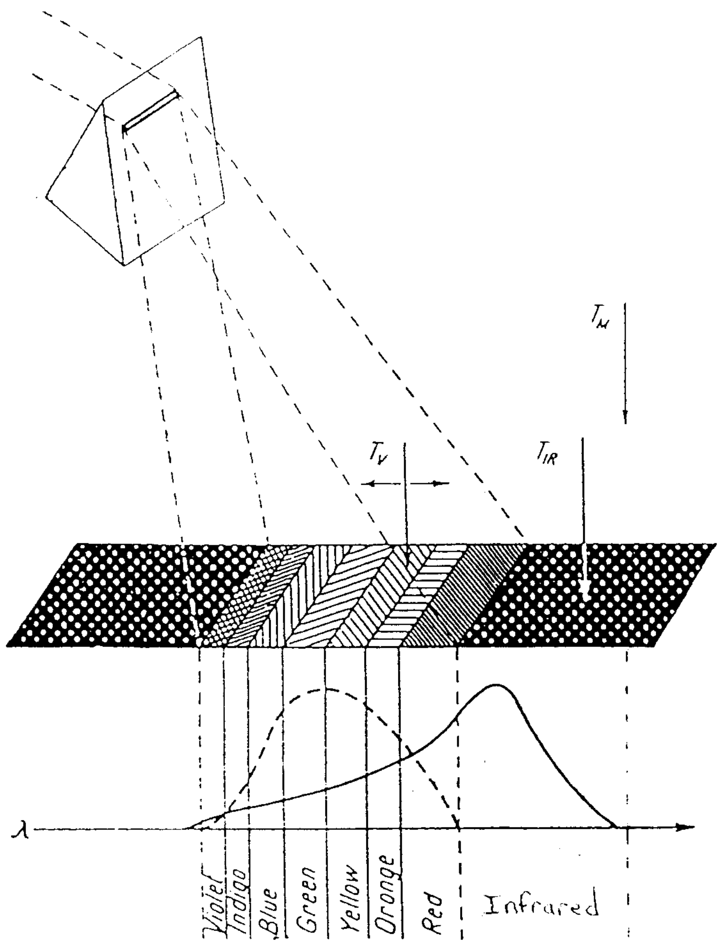


Figure 2 Herschels monochromator projecting the visible and infrared spectrums.

Source: Infrared Spectroscopy (p. 22) by M. Auram & GH. MaTeescu, 1966, New York: Wiley Interscience. Copyright 1972 by Editura tehnica Bukarest. Adapted by permission.

He used a thermometer as a detector so that he could measure the distribution of energy in sunlight. He used three thermometers each on a stand, one would be moved so its bulb was placed in each color of visible light projected by the prism. The other two were placed at each end outside the visible spectrum as controls. Much to Herschels surprise the thermometer 1/2 inch out of the visible red colored rays recorded the highest rise in temperature. In further experiments Herschel used this same arrangement to measure the spectral transmission of filters through temperature rises across the spectrum. Herschel divided the visible light spectrum into seven bands and divided the region beyond the red into six more bands (Hudson & Hudson, 1975, p. 1).

It was this discovery of the existance of invisible radiations characterized by thermal properties, were pointed out for the first time. These radiations were called thermal radiations until 1869 when Bequerel used the term infrared (Auram & MaTeescu, 1966, p. 38). Thus it was the thermometer that was the first infrared detector.

The thermometer used was lent to Herschel by Alexander Wilson, professor of Practical Astronomy at the University of Glasgow. It was referred to by Herschel as Wilson's No. 1 and was nothing more than a mercury-in-glass type thermometer with a 1/8 inch diameter ball. The thermometer had been carefully blackened with lampblack and was fitted with a small ivory scale marked to 100 degrees Fahrenheit (Hudson & Hudson, 1975, p. 2). The thermometer was the first of three types of detectors dependent on the heating effect of incident radiation that were to dominate the infrared detector field until World War II.

The second type of detector to be developed began in 1821 when Seebeck discovered the thermoelectrical effect and by 1826 demonstrated the first thermocouple. Seebecks thermocouple consisted of a pair of junctions between two dissimilar metals. When one junction was warmed by incident radiation an electromotive force (EMF) was established and a current flowed in an external circuit (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 4; Hudson & Hudson, 1975, p. 2). This development led to L. Nobili's 1829 invention of the radiation thermocouple. Figure 3 represents the basic design of a radiation thermocouple.

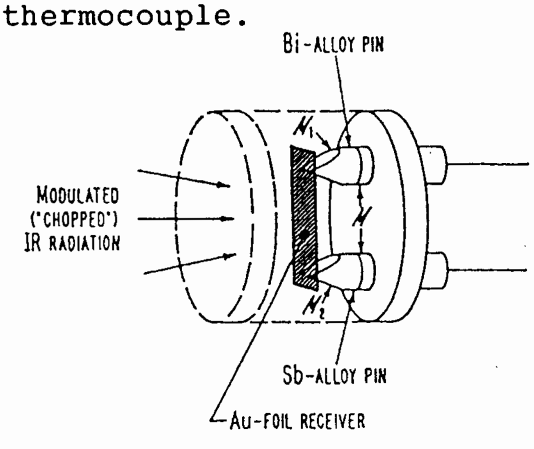


Figure 3 Pin type Thermocouple.

Source: Infrared Radiation (p. 32) by I. Simon, 1966, Princeton: D Van Nostrand. Copyright 1966 by D Van Nostrand. Adapted by permission.

In 1833 Macedonio Melloni, professor and director of the Institute of Physics at the University of Parma, modified Nobili's design by connecting in series thermocouples which came to be known as thermopiles. Melloni's thermopile is illustrated in figure 4.

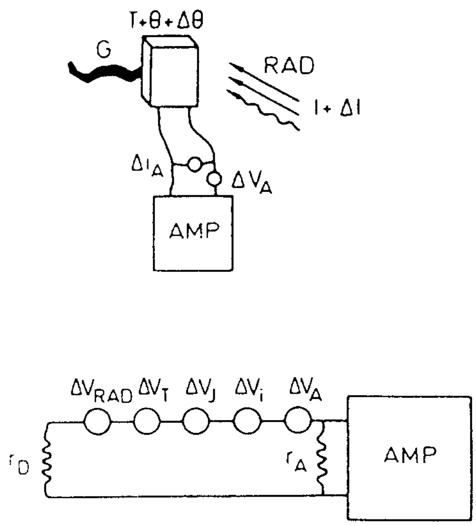


Figure 4 Melloni's thermopile.

Source: Optical and Infrared Detectors (p. 79) by J. Keyes, 1977, New York: Springer-Verlag. Copyright 1977 by Springer-Verlag. Adapted by permission.

This design called the "thermo-multiplicateur" or also known as Melloni's thermopile, used an array of bismuth and antimony blocks assembled to form a 1cm cube. The blocks were connected with 38 pairs of junctions on opposite faces of the cube. The junctions of one face were coated with lampblack and produced and EMF with the non-coated opposite face when exposed to radiation. By seriesing the cubes together the output voltage was increased to a more measurable level. Also the higher resistance produced a better impedance match with the galvanometer, which was the primary electrical measuring device used until the 1930's (Simon, 1966, p. 32; Wright, 1973, p. 43). Melloni's thermopile claimed to be 40 times more sensitive, and quicker responding than the best available thermometers (Hudson & Hudson, 1975, p. 3).

Melloni continued his studies in the area of transparency of optical materials. He found that conventional optical glass reflected infrared radiation. In his search for better materials he found that rock salt (Na Cl) to be truly transparent through out most of the infrared spectrum. Rock salt remained the principle optical material for infrared optics for over one hundred years. It was not until the 1940's when synthetic crystals were mastered that better materials were developed (Simon, 1966, p. 52; Hudson & Hudson, 1975, p. 3).

In the early part of the 1800's after Herschels discovery of infrared radiation many researchers influenced the technology. In their attempts to understand the laws of the infrared spectrum the basic ground work was laid to improve infrared detection devices that could accurately measure further and further into the infrared spectrum.

Young in 1802 determined a measurement technique that would correctly determine infrared wavelengths. In 1833 L.

Richie experimentally established the validity of a fundamental law of thermal radiation. This law established that material which is a good emitter of infrared radiation is also a good absorber. This law was further expounded upon by G. Kirchhoff in 1859 and bears Kirchhoffs name. Herschels son Sir John Herschel added to the understanding of infrared radiation in 1840 by demonstrating the existence of infrared absorption and transmission bands. This was done by noting variations in the rate of evaporation of alcohol on blackened paper on which the solar spectrum was projected (Hudson & Hudson, 1975, p. 3).

The third type of thermal detector developed after the thermopile was known as the bolometer. Samuel Langley devoted most of his professional life to the study of energy received from the sun and its effects on earths temperatures. Langley set out to measure the atmospheric transmission using Melloni's thermopile but it did not have the right shape or sufficient sensitivity for his application (Hudson & Hudson, 1975, p. 3).

As a result he invented the bolometer, which was designed to measure the change in electrical resistance and current flow of certain materials as their temperature changed. The first bolometer consisted of two thin ribbons of platinum foil, connected to form two arms of a wheatstone bridge. These ribbons were blackened on one side and arranged so one could be exposed to the radiation while the other was shielded from it. As the radiation warmed the strip there was a small change in its resistance. The change in resistance was monitored by a galvanometer monitoring a constant voltage across the bridge. When the strip changed resistance the bridge became unbalanced, causing a deflection in the galvanometer (Hudson & Hudson, 1975, p. 4). Figure 5 represents the wheatstone bridge circuit of Langley's bolometer.

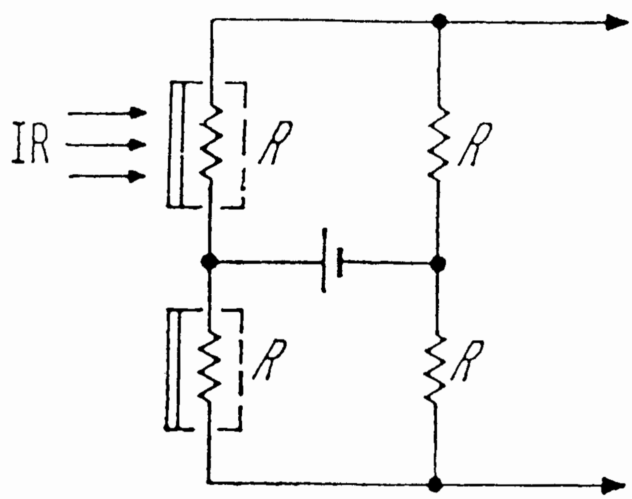


Figure 5 Bolometer bridge circuit.

Source: Infrared Radiation (p. 36) by I. Simon, 1966, Princeton: D Van Nostrand. Copyright 1966 by D Van Nostrand. Adapted by permission.

Langleys bolometer was about 15 times more sensitive than the best contemporary thermopiles. For the next 20 years Langley improved the bolometer many times over and by

1900 they were 400 times more sensitive than his original detector (Hudson & Hudson, 1975, p. 4). This improvement in the bolometer also was an important catalyst in the infrared field. Up to this point detectors had only been able to detect in the 1 to 2 μm region of the spectrum, with the bolometer this detector expanded measurements to 18 m (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 8).

Dramatic increase in sensitivity stimulated renewed research in thermocouples and thermopiles. It was found that there was no theoretical difference, but that the difference was caused by the galvanometers used. Efforts where then focused on these measuring tools and as a result by 1910 thermocouples had replaced thermopiles and there was little difference in either sensitivity or speed of response between bolometers and thermocouples (Hudson & Hudson, 1975, p. 5). Moll and Burger in 1925 developed a way to amplify the response of the galvanometer by a factor of 100. In their design of using two galvanometers coupled thru mirrors they found fluctuations in the output of detectors that could not be eliminated. This was considered the first observation of what was termed noise and is inherent in all infrared detectors (Hudson & Hudson, 1975, p. 5).

Noise is characterized by its random fluctuations in amplitude, frequency, and phase in infrared detectors. There are four principle kinds of noise; Johnson noise, current noise, shot noise, and radiation noise. In 1928 J. Johnson and H. Nyquist calculated thermal fluctuations of electron density in a conductor thus being designated Johnson noise. Current noise appears as a voltage fluctuation when current flows through a conductor. W. Schotlky in 1918 observed shot noise arising from electric charges being transported by elementary particles of a discrete charge. Radiation noise results from the fluctuations of radiant energy as it is received and re-emitted by the detector (Simon, 1966, pp. 47-50).

Although Herschel showed that infrared radiations obeyed some of the same laws as visible light, he was still convinced that he had discovered a new type of radiation. J. Forbes showed in 1834 that heat radiation can be polarized in the same manner as light. Acceptance of infrared as a part of the light spectrum began to come about from the studies of A. Fizeau and J. Foucaitt in 1873 while determining the wavelength of near infrared waves. Not all researchers pursued the thermal detection of infrared radiation (Simon, 1966, p. 8).

In 1843 E. Bequerel found that radiation in the 1μm region produced phosphorescent and photographic effects. William Smith found in 1873 that the resistance of selenium decreased when exposed to light. This phenomenon known as the Photoconductive Effect, lowered electrical resistance in some materials without a temperature change, when exposed to infrared radiation. By 1880 W. Abney was able to produce photographic plates which were sensitive to the 2μm region in the spectrum using the photo effect (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 4). These discoveries not only extended the detection range farther into the infrared region but also influenced the ideas of Photon Theory, Photoemissive Theory, and Photographic techniques used in detecting radiations.

In 1862 J. Maxwell proposed the Electromagnetic Theory of radiation which predicted the existance of electromagnetic waves and proposed the identity of these waves with light waves (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 44; Simon, 1966, p. 8). In studying Maxwells electromagnetic theory H. Hertz produced electromagnetic waves in the laboratory in 1887. He confirmed that electromagnetic waves propagate with the same velocity as light and have the same polarization properties (Simon, 1966, p. 8). Hertz's work supported that there was no essential difference between thermally and electrically produced electromagnetic waves. These same experiments were also instrumental in giving support to the particle theory in the photon behavior of radiation. Hertz found that when radiation fell on an air gap, the gap conducted electricity more easily, due to the photoelectric effect where radiation of short wavelengths can ionize atoms (Hudson & Hudson, 1975, p. 6).

From these findings scientists were trying to explain wavelength distribution of thermal radiation. W. Wien was able to establish a functional relationship between temperature and wavelength intervals (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 6). In analyzing this phenomenon M. Planck in 1900 proposed the quantum theory, which characterized radiation emissions as discontinuous and exchange of radiant energy as quantifiable. This theory supported much of the experimental evidence that had been found in studying infrared prior to this time. Albert Einstien used this concept in his theory of photoelectric effects and in 1903 he established validity in the quantum theory. Einstiens photoelectric effects also established the idea of light quanta as a modern form of Newtons light corpuscles (Simon, 1966, p. 10).

From this point on radiation or light could be considered either as a wave or as a shower of particles, depending on the interaction with matter (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 6). Thus the nature of light and radiation followed two different theories, each of which described some, but not all of the observed facts found in the 19th century. This also brought a different approach to infrared detection mechanisms. In the search for more rapid and sensitive detection methods detectors began to be developed which measured the particle characteristics of thermal radiation. These detectors known as photon detectors did not rely on the heating effect of infrared, but relied on the photoemissive, photoconductive, and photovoltaic effects that had been observed while studying infrared radiation in the 19th century (Kruse, McGlauchlin, & Mc Quistan, 1962,p. 7).

Photon Detection

Photon detectors were divided into two categories called Photoconductive and Photovoltaic devices. Both perform the same function of directly converting incident photons into conducting electrons within a detector material (Keyes, 1977, p. 9). They both produce an electrical signal that represents the unit radiant power which is proportional to wavelength (Keyes, 1977, p. 17).

The photoconductive effect simply involves applying a bias voltage across a detector material which generates a current proportional to the photo-excited electron concentration. A Photovoltaic effect occurs in a material where there is a space charge layer formed by a Schottky barrier of a p-n junction (Burnay, Williams, & Jones, 1988, p. 8; Spiro & Schlessinger, 1989, p. 166). The basic design and outputs of photoconductive and photovoltaic semiconductor detecting materials are shown in figures 6 and 7.

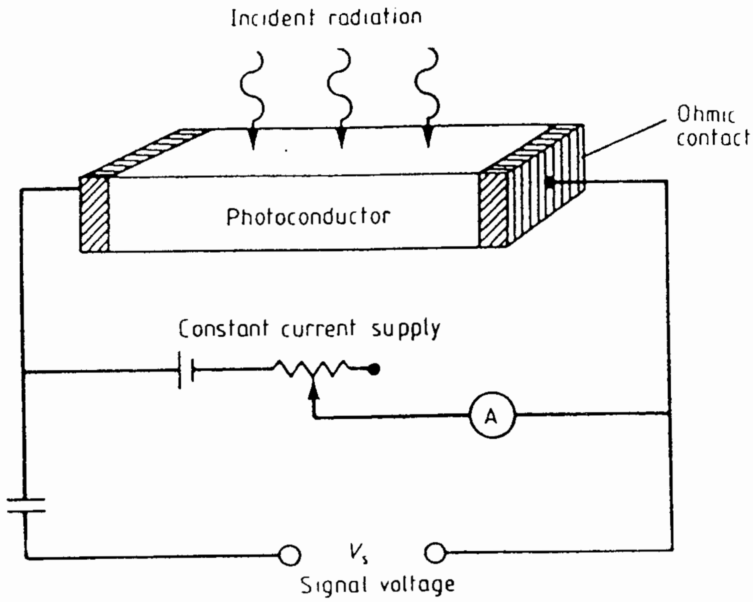


Figure 6 Operating principles of a photoconductor.

Source: Applications of Thermal Imaging (p. 9) by G. Burnay, T. Williams, & C. Jones, 1988, Philadelphia: Adam Hilger. Copyright 1988 by Adam Hilger. Adapted by permission.

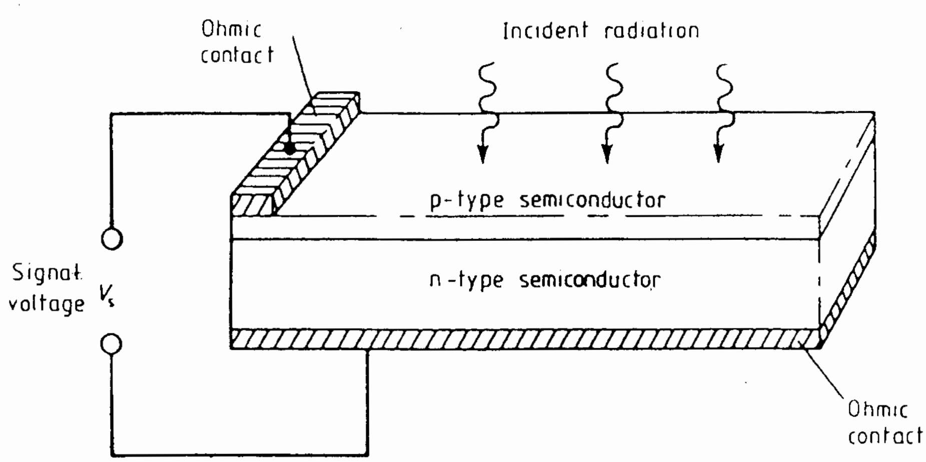


Figure 7 Schematic of a p-n junction photovoltaic diode.

Source: Applications of Thermal Imaging (p. 9) by G. Burnay, T. Williams, & C. Jones, 1988, Philadelphia: Adam Hilger. Copyright 1988 by Adam Hilger. Adapted by permission.

Photoconductivity is further broken down to being intrinsic or extrinsic for all semiconductors. Intrinsic photoconductivity excites a free hole-electron pair by a photon whose energy is at least as great as the energy gap of the detecting material. Extrinsic photoconductivity occurs when an incident photon lacks sufficient energy to produce a free hole-electron pair, but produces excitation from a detector material that has been doped with an impurity in the form of a free electron bound hole or electron (Keyes, 1977, pp. 9-15).

In 1917, Theodore Case introduced the first Photon detector for the military, using a thallous sulfide material in a photoconductive infrared detector (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 6). The incident photons of the infrared radiation interacted directly with the electronic materials of the detector. There was no heating involved with this detector which established the parallel paths of infrared thermal detectors. One type of detector used heating absorption principles for detection of radiation, while the other used particle excitation or wave detection of radiation. Case's detector was capable of extending to only about 1.4 μm in the infrared spectrum, but its response time and sensitivity were superior to thermal detectors (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 7).

With the development of the photon detector most research began to be focused in this area. Gudden and Pohl working in Germany brought forth an understanding of how thallous sulfide cells worked. With this new understanding by the 1920's many scientists from France, Italy, Japan, and Germany were conducting research on thallous sulfide photoconductive detectors (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 7). From this point on the Germans carried on extensive studies in infrared systems although this was done under great secrecy and information was not shared until after 1945.

In 1933 Edgar W. Kulzscher doing research for the German Army at the University of Berlin, discovered that lead sulfide was also photoconductive and expanded detection into the 3 μm range. Under the direction of Werner K. Weilhe, Germany produced a infrared system known as Kiel IV that was used in airborne systems during the war (Hudson & Hudson, 1975, p. 8).

In 1939 just prior to World War II, Robert J. Cashman, a professor of Physics at Northwestern University was the only individual in the United States working on photoconductive detectors. Cashman was successful in solving the problems found in producing thallous sulfide cells, and also continued studying other possible detecting materials (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 7; Hudson & Hudson, 1975, p. 8). The Office of Scientific Research and Development in

1941, contracted Cashman to produce thallous sulfide detectors. By 1943 he had produced 800 of these detectors and in 1944 commercial production began. These detectors operated best in the 0.95μm range, although they extended to 1.45μm range (Hudson & Hudson, 1975, p. 8). These detectors were 1000 times more sensitive than thermocouple type detectors. Cashman also discovered in 1944 lead sulfide as a detector material and by 1945 Cashmans detectors were equal to or better than German detectors. These detectors operated in the 2.5 to 3.6μm range, although the Germans found that they could extend this range further by cooling these detectors. By using dry ice they could lower the cell temperature to 195°K, making these detectors more sensitive than those operating at room temperature (295°K). These cooled detectors extended the operating range to 3μm and by using liquid nitrogen this could be extended to the 4μm range (Hudson & Hudson, 1975, p. 9).

The photon detectors were well on their way to becoming the forerunners of todays infrared thermal imaging systems also known as infrared thermography. The major problem with the photon detectors was that to reduce the noise factors to an acceptable level for signal processing, meant that cooling to 90°K or below was needed (Hudson & Hudson, 1975, p. 343).

This opened a new area of research for infrared detectors known as Cryogenic cooling. The four most important operating temperatures used in cooling are room temperature 295°K, dry ice 195°K, liquid nitrogen 77°K, and liquid helium 4.2°K (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 393). Today by using the Peltier effect thermoelectric cooling can be created. The Peltier effect occurs when current passing through the junction of two metals in a semiconductor, is reversed which causes a change from production of heat to absorption, hence causing a cooling phenomenon to occur (Burnay, Williams, & Jones, 1988, p. 15).

Also during this time research continued trying to find better electrical conducting materials. Hence the age of modern semiconductors was being born. In 1947 William Schockley, John Bardeen, and Walter Brattain developed the semiconductor transistor, this sparked large scale research and development into the band structure and transport processes of semiconductors. This also sparked huge funds by the government and industry to develop infrared technology which affected every aspect of infrared detection for the next 30 years (Keyes, 1977, p. 1).

Between the years of 1952 to 1965 H. Levenstein and his students at Syracuse University disclosed an entire family of germanium semiconductor materials extending detection to 8 μm for gold, 12 μm for mercury, 24 μm for copper, and 35 μm for zinc dopants used with germanium materials (Spiro & Schlessinger, 1989, p. 158). By 1959 W. Lawson in England found that trimetal combinations could produce better detection of radiation with his lead-tin-telluride material, but this combination is all but abandon today. In the mid to late 1960's doped silicon materials were found to produce good detection characteristics (Spiro & Schlessinger, 1989, p. 160).

Thermal Detection

Even with the advancements in photon detectors and semiconductor materials efforts to improve and design thermal detectors continued. Thermal detectors did not require cooling and operated at room temperature 295^{c}K although research found that cryogenics could be applied to thermal detectors also (Simon, 1966, p. 38). In 1946 W. Brattain and J. Becker at Bell Telephone Laboratories developed the first semiconducting bolometer using a thin flake of mixed metal oxides. It was not until 1961 that cryogenic cooled bolometers where successfully introduced using gallium doped germanium by F. Low of Texas Instruments. This was the first infrared detector to be used in space (Simon, 1966, p. 38).

Another type of thermal detector that became popular in infrared detection appeared in 1947 as a type of gas thermometer called the Golay Cell. The Golay cell was designed to allow infrared radiation to heat a small amount of accluded gas, causing a flexible mirror to be distended. This movement was detected by the change in intensity of light reflected from the mirror to a photocell (Kruse, McGlauchlin, & Mc Quistan, 1962, p. 8; Keyes, 1977, p. 89). This type of detector is still one of the most sensitive room temperature detectors, but its bulkiness, sensitivity to vibration, and rather slow response time tend to limit it to laboratory applications (Keyes, 1977, p. 89). The basic design of a Golay Cell is shown in figure 8.

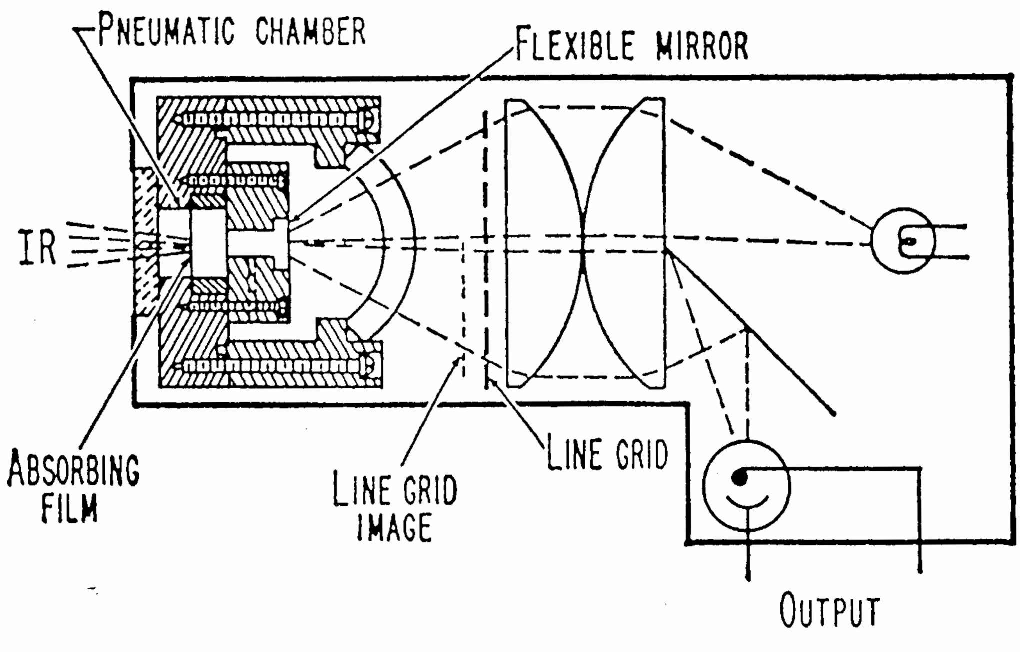


Figure 8 Golay pneumatic detector.

Source: Infrared Radiation (p. 30) by I. Simon, 1966, Princeton: D Van Nostrand. Copyright 1966 by D Van Nostrand. Adapted by permission.

Just prior to World War II a new type of thermal detector called a Pyroelectric detector was proposed, but it was not until the late 1960's and early 1970's that real interest was taken in them as a thermal imaging device. With the increase in better semiconductor detecting materials and a growing need for uncooled detectors with better performance suitable for military and industrial uses did this detector gain popularity (Keyes, 1977, p. 90).

Pyroelectric materials are those low in crystalline symmetry and possessing internal electric charges on crystal faces. These charges appear in equal and opposite quantities on parallel faces and so constitute dipoles (Wright, 1973, p. 44). Even quite slow changes in temperature produce changes in the internal dipole moment and produce a measurable change in surface charge. Hence pyroelectric detectors impedance is almost that of pure capacitance. As a result an output signal will only appear when input radiation is changing (Keyes, 1977, p. 90).

The operating principles of the pyroelectric detector are demonstrated in figure 9.

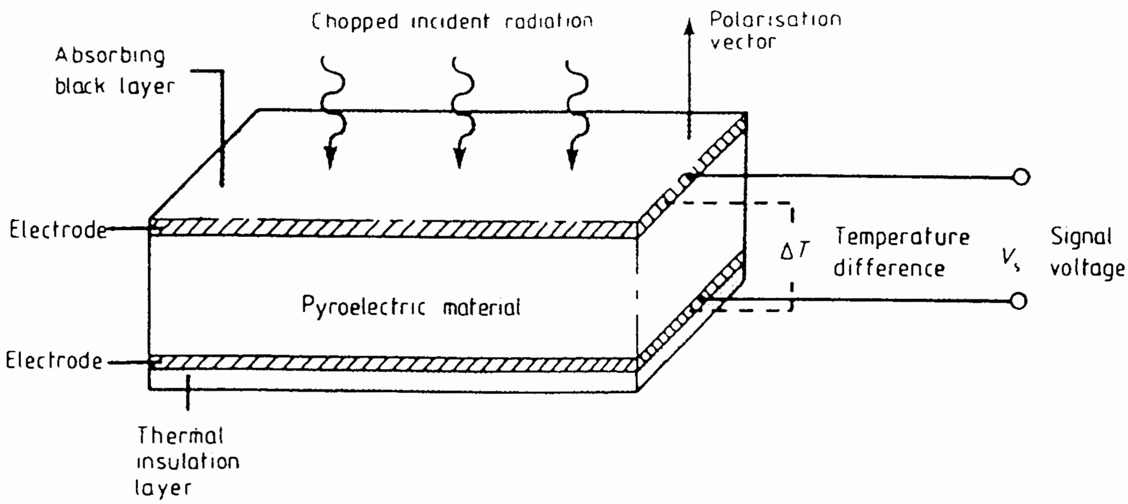


Figure 9 Operating principles of the pyroelectric detector.

Source: Applications of Thermal Imaging (p. 6) by G. Burnay, T. Williams, & C. Jones, 1988, Philadelphia: Adam Hilger. Copyright 1988 by Adam Hilger. Adapted by permission.

By 1965 infrared systems began to grow in the commercial markets. These systems were not just thermal detectors as in the past but incorporated thermal imaging techniques that could converted a scene's radiation pattern into a realtime visual image.

Thermal Imaging

The earliest thermal imaging system was known as the evaporograph which employed a thin film of oil supported on a blackened membrane. As the image was focussed on the membrane a differential evaporation of the oil film occured. The film was then illuminated with visible light producing a thermal picture (Keyes, 1977, p. 96). Other attempts were made to produce variations of the technology but as a whole these systems were slow, insensitive, and subject to random fluctuations. For these reasons they have only seen limited uses for specialized applications (Chantry, 1984, p. 644).

One of the earliest thermal imaging systems that was successful for commercial use was the pyroelectric vidicon introduced by J. Cooper in 1962 (Ravich, 1986, p. 104). The pyroelectric vidicon used a scanning system that modulated at the same frame time as television.

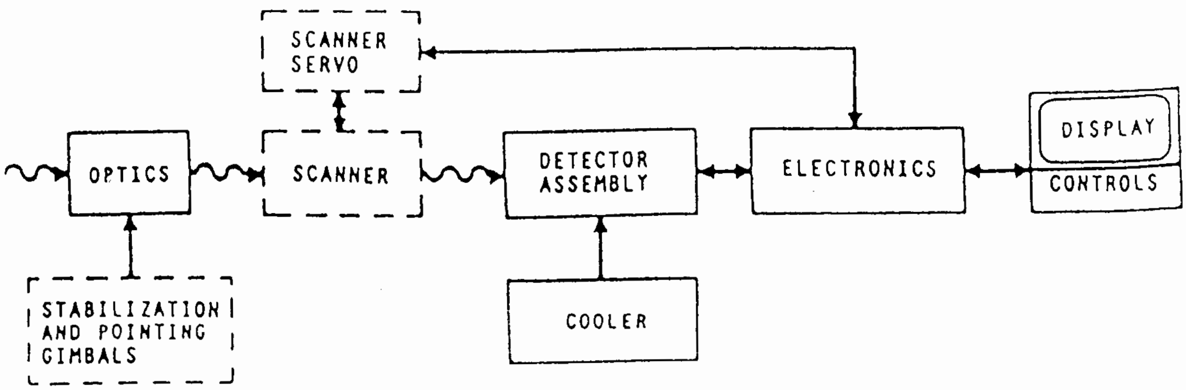


Figure 10 Thermal imaging system.

Source: Infrared Technology Fundamentals (p. 208) by I. Spiro & M. Schlessinger 1989, New York: Marcel Dekker Inc. Copyright 1989 by Marcel Dekker. Adapted by permission.

Thermal imaging brought forth many uses in civil, industrial, medical, scientific, and military applications.

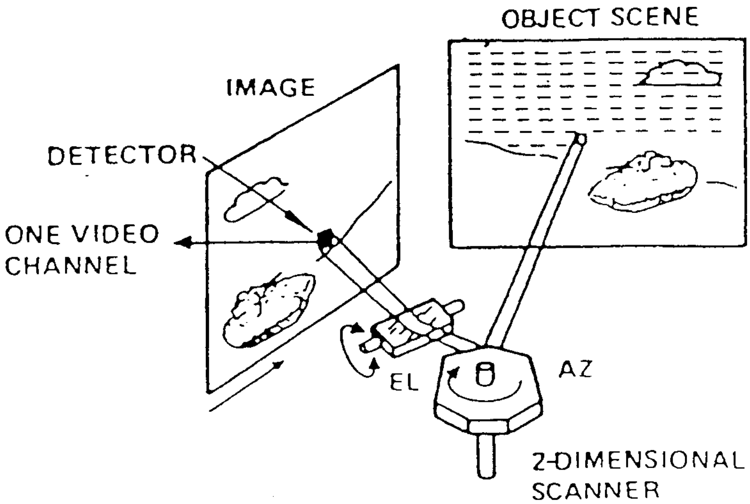
The maximum radiative emission for thermal imaging purposes are found in the 2 - 15μm region of the electromagnetic spectrum. These systems allow a total passive technique requiring no external illumination and produce a real-time image from safe distances. They detect different temperature levels within a scene and are unaffected by smoke or mist when detecting obscured objects (Burnay, Williams, & Jones, 1988, p. 1). Figure 10 represents a block diagram of typical thermal imaging systems.

In their simplest form thermal imagers consist of a lens that allows the radiation from the scene to strike the heat sensitive or photon sensitive material. The change induced on this material is then processed and displayed in a visual form. The number of points displayed in a picture is dependent on the imagers design. Some systems use a optomechanical scanning device imaging different points in the scene onto the detector material sequentially in time (Burnay, Williams, & Jones, 1988, p. 21). Although some sensitivity is given up the ability to produce thermal images works well. Thermal images arise from the temperature variations and differences emitted in a scene and these differences may be fractions of 1°C with a mean scene temperature of about 195°K. Hence the contrast is small compared to visible image contrasts. The contrast of an object in a 290°K scene is about 0.039 in the 3 - 5μm band region and 0.017 in the 8 - 13 μm band region. This gives objects in the 8 - 13 μ m band region sensitivity but the 3 -5 μ m region will give greater contrast (Burnay, Williams, & Jones, 1988, p. 4).

Thermal imagers are excellent in creating a qualitative determination of surface temperatures, although absolute temperature measurement introduces a margin of error. Radiation received from an object will be a function of not only its temperature but also of spectral emissivity, reflections of surrounding objects in the atmosphere, transmissions through the imagers optics, the detectors spectral response, and emissions by the scanner (Burnay, Williams, & Jones, 1988, p. 5). Still the imagers on the market today are accurate within 0.1° C.

To achieve maximum thermal sensitivity the ideal situation would be a two dimensional array of detectors representing a one to one correspondence equivalent to the number of picture points to be displayed in a scene. Arrays of this type are know as starring arrays. However even with todays technology sufficient fields of view have not been designed to be used in most applications. As a result most detectors use small arrays which are scanned over a scene multiple times to generate a complete field of view (Burnay, Williams, & Jones, 1988, p. 4). Scanning patterns used in these systems influence the signal output. There are three basic patterns used, serial giving a uniform image, parallel scanning allows a lower scan speed, and a serial-parallel pattern incorporating both characateristics is most generally used.

A 2-dimensional serial scanner is depicted in figure 11.



ADVANTAGES	DISADVANTAGES
SMALL APERTURE SCANNER, DEWAR, DETECTOR	HIGH SCAN SPEED
MINIMUM NUMBER OF ELECTRONIC CHANNELS	LARGE SIGNAL BANDWIDTH
IMAGE UNIFORMITY, REFERENCE LEVEL	
OUTPUT DIRECTLY TV COMPATIBLE	

Figure 11 Serial Scanning.

Source: Infrared Technology Fundamentals (p. 211) by I. Spiro & M. Schlessinger 1989, New York: Marcel Dekker Inc. Copyright 1989 by Marcel Dekker. Adapted by permission.

A new type of photoconductive detector known as the Signal Processing In The Element (SPRITE) incorporates within the material a scanning function. This detector operates in the (3-5) and (8-13) μm region and is made of a cadimum-mercury-telluride material. This detecting element performs the same function as a row of serial detectors and the time delay integration occurs within the element itself (Burnay, Williams, & Jones, 1988, p. 11).

The signal output from these detector elements were then amplified and transmitted to the signal processing units in the system. These signals were processed by the electronics into the proper format and frame rate for TV display (Spiro & Schlessinger 1989, p. 209). In the electronics these signals compile, manipulate, and store images using powerful microprocessing computers. As an end result real-time video quality pictures of a scene were output to a TV, or were digitized and stored on a disk media.

Figure 12 represents modern detectors using sprite detectors and electronic video design.

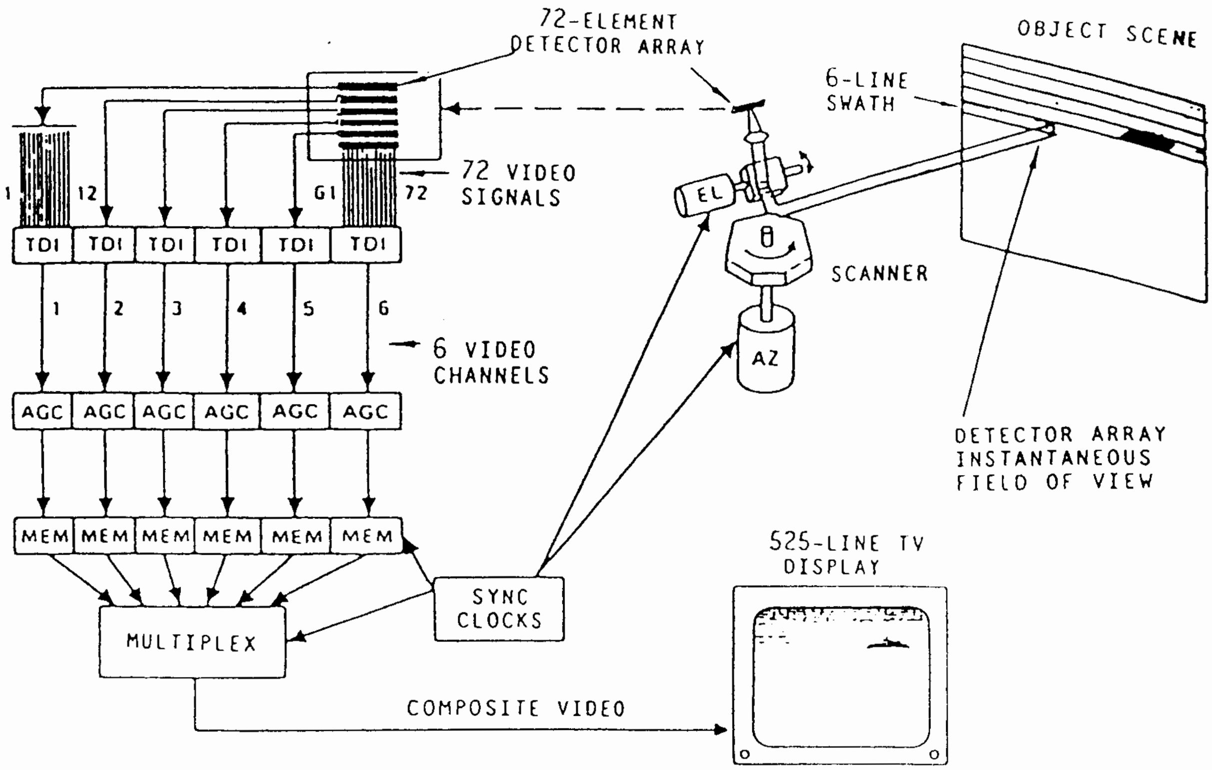


Figure 12 Matrix array system.

Source: Infrared Technology Fundamentals (p. 214) by I. Spiro & M. Schlessinger 1989, New York: Marcel Dekker Inc. Copyright 1989 by Marcel Dekker. Adapted by permission.

By the end of the 1980's infrared imaging systems had become fully solid state units offering new applications of use. These systems not only provide a means for discerning and measuring temperature differences in a scene or object, but can be useful in determining other information over time. There are many advantages that industry can gain with these systems. They require no external illumination, they can detect different hot or cold emissivities within a scene, they can dectect thru smoke or mists, there is no direct contact with an object needed, measurments can be made from outside hazardous areas, they are capable of following rapid temperature changes, they are capable of measuring ranges from -20 to + 2000 ° C, data can be recorded and processed on video and computer-based processing systems, many different points can be monitored at the same time, and this equipment is easy to transport and use (Spiro & Schlessinger 1989, pp. 206-210; Burnay, Williams, & Jones, 1988, pp. 36-38).

CHAPTER IV

CONCLUSION

Based on the information found in the literature research, the thermal imaging systems on the market today are capable of accurately detecting temperature and surface temperature changes in electrical motors. The literature also indicated that Infrared thermography equipment and techniques are an excellent tool that could be easily incorporated into predictive maintenance programs. What was not found in the literature was research data on using infrared imaging to monitor electric motor failures. Therefore experimental research focusing on electric motor failure still needs to be run using infrared imaging systems to monitor temperature changes.

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