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THE ROLE OF FIBEROPTICS IN REMOTE TEMPERATURE MEASUREMENT

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INTRODUCTION

The use of optical fibers in conjunction with infrared detectors and signal processing electronics represents the latest advance in the field of noncontact temperature measurement and control. Infrared (IR) detectors have been around for many years, although R & D keeps adding to their numbers and performance characteristics.

Optical fibers are much younger and only recently have become the object of widespread interest, thanks to their ability to carry over long distances optical information signals.

Generally, IR detectors have been used in conjunction with conventional optical elements (lenses, mirrors, presumes). Fiber optics were excluded from consideration because they are made of either glass or plastics, both of which are opaque throughout most of the infrared spectral region. Thus, according to fundamental laws of physics, their marriage to infrared detectors could never work.

Defying all theoretical predictions, coupling fiber optics with infrared detectors resulted in several new families of instrumentation and control systems endowed with superior performance characteristics. How is this possible? Let us view the process step by step. For those not familiar with infrared, we shall start with the fundamentals.

INFRARED RADIATION

IR radiation, sometimes called thermal radiation, is the electromagnetic radiation occupying the spectral area between visible light and the radio microwaves (Figure 1). Infrared radiation is emitted by all physical matter, as a function of temperature and of emissivity, which is a numerical coefficient of proportionality related to the amount of electromagnetic power radiated by a blackbody at the same temperature.

Like visible light, IR radiation is made of photons carrying energy away from its source (the surface of a physical body) and traveling at the speed of light. The power emitted in this process is proportional to the fourth power of the absolute temperature of the emitting surface, as shown by Stefan-Boltzmann's equation (Figure 2):

$$W = EoT4$$

where W = radiant flux emitted per unit area (W/cm2)
E = emissivity (unity for blackbody source)
o = Stefan Boltzmann constant (5.673 x 10-12 W/(cm2)(K4))
T = absolute temperature of source (K4)

The power so emitted is of "incoherent" type, which means that the radiation takes place simultaneously at all wavelengths of the infrared spectrum. This is due to the fact that the emitting surface is made of an extremely large number of different "oscillators" (molecules, atoms and subatomic particles), which vibrate, rotate, oscillate and "jump" at their own resonant frequencies.

Intuitively, it is easy to understand why the higher temperature, the higher the infrared energy emitted by the source. Heat is directly related to the degree of molecular and submolecular motion: the more violently these physical particles move, the higher is the energy content of the photons emitted.

However, the power content of this radiation is not constant throughout the infrared spectrum, but its distribution varies as a function of wavelength and temperature. Figure 3 shows the blackbody radiation curves, that is, the distribution of infrared power emitted by an ideal surface having an emissivity factor E = 1. In the illustration, the slanted line indicates how the wavelength of the peak emission moves towards the visible region of the spectrum as the temperature of the emitting surface increases. This explains why physical matter becomes incandescent at high temperatures. Figure 4 shows the correlation between temperature and the wavelength of the peak emission.

BLACKBODY AND EMISSIVITY

It has been mentioned that the blackbody's emissivity is equal to unity. Blackbody is a term indicating an ideal surface having an infinite number of oscillators, one for each wavelength of the infrared spectrum. All the infrared radiation laws are formulated and are true for the blackbody. In practice, no such ideal body exists because every material emits infrared radiation according to its physical composition and characteristics. The degree to which this emission approximates the blackbody's emission is expressed as a fraction of unity and is called emissivity. Its symbol is E. From Stefan-Boltzmann's equation we see that once E is known, it is possible to establish a direct correlation between the power radiated by a physical surface and its temperature.

The concept of emissivity is not very easy to grasp; however, perhaps a comparison with the properties of visible light might help. Consider, for instance, an opaline electric bulb emitting white light. Set on "unity" the amount of light radiated. If the bulb is now painted in red, blue or any other color, the amount of light radiated shall be a fraction of the unity emitted when the bulb was white, could call it "emissivity," and it will always be less than unity.

In the infrared domain, the blackbody could be compared to the just-mentioned white bulb, while we could think of any other surface as emitting "infrared colors." And we should also include the color gray, with the only difference that the gray radiation covers the whole infrared spectrum (just as blackbody, only at a lower level) while the other "colors" are only covering a portion of the total infrared spectral area.

Unfortunately, often E is not known, either because it is a variable difficult to control, or simply because it is inconvenient to measure. In such instances, the ratio radiometer offers a practical solution. Its operation is based on the assumption that the incoherent radiation emitted by a nonblackbody curve in shape and wavelength with only the difference of being "dropped" to a lower level in the power scale (Figure 5).

For many surfaces, this assumption can be taken as true in first approximation. Consequently, every temperature of the target is precisely identified by a unique value of the ratio of conveniently chosen and independent from the level at which the corresponding graybody emission curve has been dropped.

Several versions of ratio radiometers have been developed, but until recently their operation was limited to the high-temperature region because of the difficulty of collecting enough radiant energy at the chosen wavelengths when using conventional optics, which necessarily have a small aperture number.

Conversely, the use of fiber optics, which have a remarkably larger aperture number, makes it possible to gather enough energy to allow measurement of much lower temperatures. At the time of this writing, approximately 200oC is the low-end temperature measurable with the most advanced fiber-optics ratio-radiometers. They are quite useful in a host of applications because they measure the temperature of a target independently from the emissivity value of its surface emissivity is not known, or when it varies during the measurement process due to changes in surface characteristics, such as oxidation and crystallization.

THE INFRARED RADIOMETER

Figure 6 is the basic block diagram of all single-channel infrared radiometric systems. The elements shown in solid lines are always present, while the ones shown in dotted lines are optional, their presence and features being dictated by the system's performance requirements. Ratio detectors and multichannel systems include additional blocks, generally of the same type.

In essence, these systems turn the infrared radiation emitted by the object located in their field of view, into an electrical signal that, after due processing and manipulation, can, in real time (1) be displayed as the temperature of the target, with the desired degree of resolution (both thermal and spatial); (2) be recorded and/or stored in any of several existing ways; and (3) through a feedback loop, control the process to which the target is subjected, for instance heating or moving, etc. The following sections review in more detail the most important elements shown in basic block diagram.

THE OPTICS

Until recently, the optics used in infrared radiometry were of the conventional type, such as lenses and prisms. They are very similar to their corresponding elements with the visible radiation, the major difference being the optical materials of which they are made, which must have good transmissivity in the infrared spectral area.

Figure 7 shows the transmission spectral regions of a number of optical materials. These transmission regions are commonly called "windows," and their limits are indicated for a minimum of 10% external transmission and 2 mm of sample thickness.

In addition to refractive elements, such as lenses, reflective surfaces either flat or curved are frequently uses as optical elements handling IR radiation. The major advantage is their total freedom from chromatic aberration, which is a particularly serious difficulty in the infrared spectrum because the refractive index varies with wavelength, and the spectral area of interest is generally very broad.

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Optical Fibers

Optical fibers are transparent linear elements inside which radiation propagates by total internal reflection. Figure 8 show the physical principle on which the fiber operation is based. All the fibers used in infrared instrumentation are made of glasses especially chosen for their ability to transmit the radiation comprised in the chosen spectral region.

The illustration shows that after entering the front surface, all rays that acquire an inclination smaller than the critical angle are totally reflected inside the fiber core and keep traveling in this fashion until they reach the opposite end or are totally absorbed, whichever comes first. For a fiber having a critical angle of 67o, the illustration shows an acceptance angle of 70o, which means that all rays incident onto the fiber's front surface at a 35o angle or less with its axis are trapped inside the fiber by total internal reflection.

On the other hand, all incident rays entering the fiber with an inclination larger than the 35o angle will leave the fiber at the first contact with its internal surface. This behavior is commonly called "spilling."

The value of the critical angle is a function of the ratio between the refractive indexes n1 and n2 of the glass or which the core is made and of the medium surrounding it. Thus, by controlling the ratio n1/n2, we have a means of increasing or decreasing the acceptance angle of fiber optics, a feature that can be used to obtain special performance characteristics.

Cladding is the name of the technique used to establish a permanent n1/n2 ratio. It consists of coating the core with a layer of solid material (usually a different type of glass) having the desired index of refraction. Without this coating, two fibers touching each would "spill" light into each other since they have the same refractive index. The presence of the cladding prevents this happening.

Figure 8 shows a fiber core enveloped by a layer of cladding, whose outside surface, to the right of point P, is, in turn, coated with an absorbent layer of material. This will prevent stray rays, such as those surpassing the critical angle (for instance, where the fiber makes a curve) from spilling out: the outer coat will merely absorb them. Also, at a curve, radiation cannot get into the fiber from outside, and every chance of interference with the rays traveling along the fiber is eliminated.

How tight a curve can a fiber make without spilling? As long as the ratio of the bend radius to the fiber diameter is above 40, the losses are negligible. This means that a fiber with a 25-u core diameter can be wound around a 1-mm mandrel with no significant transmission loss.

Besides their ability to carry radiation around corners and through opaque obstacles, optical fibers provide quite large acceptance angles for incident radiation, thereby making them comparable to "fast" conventional optical systems; that is, systems having a large NA number. NA stands for numerical aperture number of an optical system and is a measure of its ability to accept incident light rays. This, of course, is a function of the limit angle of acceptance. The larger this is, the larger the cone of radiation entering the optical fiber, transmitted along its length and out of its output end.

When compared with typical radiometers, which have optical f/no generally ranging between 4 and 8, optical fibers can capture remarkably higher radiating power. On the basis of correlation of equivalent f/no, such optical fibers theoretically are more effective by factors ranging from 20 to 88. Figure 9 graphically illustrates a comparison between the cone of radiating energy collected a conventional lens and an optical fiber.

As mentioned before, the optical fibers used with infrared instrumentation are made of special glass having good transmissivity in that portion of the infrared spectrum covered by the detector used in the system. In other words, fibers and detector must be matched to each other for best system performance. Figure 10 shows the transmission losses are indicated as a percentage of the radiation signal being transmitted. In other words, the signal magnitude is inversely correlated with the length of the fiber, which means that the signal magnitude will never drop to zero, although it will asymptotically approach the zero level. However, the noise traveling through the fiber also will follow the same laws; therefore, the S:N ratio will remain the same no matter how long the fiber is. Thus, the detector noise and the self-generated noise of the signal processing electronics become the limiting factors in signal readability.

Fiber Bundles

Thus far single fibers have been discussed. For practical purposes, however, fiber bundles are most commonly used. A fiber bundle is an assembly of a number of fibers, anywhere from just a few to many hundreds, lined inside a containing sleeve that can be either rigid or flexible. In Figure 11, fiber bundles of different length and composition are shown. As can be seen from the picture, the ends of these bundles are made rigid to hold firmly in place the terminations of all the fibers. Usually this is achieved with the use of a cementing compound, such as an epoxy resin that hardens to a degree adequate to permit optical finishing of the end surfaces.

Figure 12 shows the geometric representation of an end surface of a very small bundle of fibers. The majority of those used for infrared temperature measurement applications have several hundred fibers to pick up and transmit more signal to the detector. Typically, the outside diameter of a single fiber is 25u.

Fiber bundles are divided into two groups: coherent and incoherent. The coherent ones have the same identical geometrical distribution of the fibers at the two ends. In this fashion, the light distribution picked up at the front end is exactly duplicated at the output. In other words, an image is transferred from one end to the other, with only the degradation resulting from (a) the transmission losses, and (b) the resolution allowed by the size of the individual fibers and the spacing in between.

Instead, the incoherent fiber bundles have a random distributi fibers at the two ends and no image is transferred from one end to the other. Only radiation is available at the output in quantity proportional to the total input, minus the transmission losses.

Most of the optical fiber bundles uses with infrared radiometers are of limited length, generally 1 or 2 meters long, occasionally up to 10 meters long. If they are not terminated with a lens, they have a field of 60o. This means that the diameter of the target area viewed by the detector through such optics is light larger than the distance between the front end of the fibers and the target surface. This can be easily verified by backlighting the target, which is achieved by injecting visible light at the opposite end of the surface. Figure 13 compares backlighting for two different types of fibers. The one in the right hand of the operator is terminated with a lens, and so has a focal point at a well-defined distance from it.

Fiber optics of the first type are used when the target is large, and the average temperature of the viewed area must be measured. Fibers of the second (focused) type are used for measuring the temperature of a small area when it is not possible to place the fiber's front end close enough to the target surface. The focal point for fibers of this type can be located at almost any distance from the fiber's front end, although for practical purposes this distance is usually set between 2 cm and 3 meters.

The backlighting capability assures perfect and easy target aiming, both as location and size of the viewed area, without parallax error. In some applications it might be desirable to check the fiber's aim at any time, during the operation. In this case, a bifurcated optical fiber can be used. One branch of it is connected to a high-intensity light that will go on by pressing a switch, thus allowing the operator to verify and, if needed, to achieve a perfect aiming of the fiber. The other branch will allow the infrared detector to "see" the target at exactly the same spot that was illuminated and to measure its temperature as soon as the aiming light has been turned off.

Advantages and Disadvantages of Fiber Optics

The first and major disadvantage of optical fibers is the poor transmissivity of any glass of plastic in the infrared spectral area. Radiation of intermediated and far infrared (wavelengths larger than 2.5u) is absorbed by the fibers after just a few millimeters of travel. This makes it extremely difficult to measure temperatures below 100oC, since most of the radiation emitted by a surface below 100oC is located around the 7u region. Of course, there is some radiation in the near-infrared area, but its energy content is so low that it lies buried under the noise level.

Another disadvantage of optical fibers is the impossibility if producing two bundles of identical characteristics because a bundle is made of many hundreds, and often several thousands of individual fibers, whose final number can differ by a few percentage points at the end of the manufacturing operation because of unavoidable losses due to breakage. And even if it were possible at the beginning to assemble two perfectly identical bundles, individual fiber breakage during usage would soon create a difference in their ability to transmit infrared energy. Consequently, the signal processing electronics must have the flexibility to adjust and compensate for this lack if fiber bundles consistency.

Finally, any glass has a softening thermal threshold that cannot be exceeded without damage to the fibers. This threshold for most glasses is around 600oC. Thus, fibers that are expected to operate in hotter environments must be cooled in any of several available ways (air purge, water circulation, etc.).

Concerning advantages, all fibers can be looked at as low-pass filters, with gradual cutoff of transmissivity above 2.5u in wavelength. If this is a disadvantage because it enhances thermal resolution. This is due to the fact that radiation power increments in the near-infrared area are larger than the corresponding power in the total radiation area for the same ^t of the target. The reason for it is the displacement of the peak radiation wavelength toward the visible region as the target temperature increases. Figure 14 illustrates this concept: it can be clearly seen that the area increments at the left of the vertical cutoff line are larger than the area increments of the total surface area subtended by the full radiation curves.

In second place, there is the advantage that optical fibers can be defined as "shielded radiation conduits" of constant transmissivity, no matter what environment they might have to cross. Smoke, water, vapors, dust, gases, etc. cannot affect the optical signal transmission through the fiber.

Among the other advantages are the following:

1. Inert, rugged construction. In addition to being unaffected by energy fields, optical fibers contain no moving parts and are specified and constructed for use in most heat, chemical or radiation environments. For example, they can be immersed in molten materials, such a polymer melts in extruders and injection molding machines, where direct, real-time response measurement has heretofore been impossible with thermocouples because of frictional heating and heat sinking of the heat sensing element.

2. Easy installation. Most fibers are flexible and of a size that permits bending around opaque obstacles for installation where ordinary instruments simply cannot fit. A direct line of sight is not required.

3. Simplified setup eliminates human error. All fibers can be aimed with pinpoint accuracy using a source of illumination from one end to carefully line the target area at the other end. This simple advantage overcomes most problems associated with proper alignment of conventional noncontact temperature detectors.

4. Optimum target viewing angle. With the addition of small lenses, the viewing angle of the fiber can be modified from the standard 60o cone, down to a spot 1 mm in diameter. Large or small areas are precisely monitored with optimum resolution and accuracy.

5. Wide range of temperature measurements. With the proper selection of quick-disconnect fibers, a single system may be used to cover the full range of temperatures and repeatability.

6. Very large NA. This characteristic allows one to capture from the target a very large cone of radiated energy, up to 100 times larger than it is practical with conventional optical systems.

THE CHOPPER

The majority of the IR radiometers incorporate a "chopper," that is, a mechanical device that periodically interrupts the flow of radiation from the target to the detector. In this way, the magnitude of the infrared signal can be easily measured by comparing it with the baseline of the no-signal level during the cutoff caused by the interposition of the chopper blade.

This alternating between radiation and no-radiation is reflected, at the detector output, as an alternating electrical signal, which by its own nature, is easier to produce than a dc signal. However, a minority of infrared radiometers does operate without a chopper. In this instance, the system's output is a dc signal that only varies as a foundation of the variations of the impinging radiation. The major difficulty of these systems is a signal drift.

In its most common configuration (Figure 15), a chopper is a slotted disc rotated by an electric motor. The detector's field of view is alternatively opened and closed by the slots and the blades of the disc rotating in front of it.

Lately, tuning forks have been used as choppers. Approximately designed vanes attached to the ends of the fork's tines to perform the chopping action. Chopping frequencies up to 25,000 Hz are attainable. When compared to motor-driven choppers, tuning forks have the advantage of small size, light weight, greater accuracy, long-term stability, low power drain and negligible heat dissipation.

Another class of IR radiometers operating without chopper are the scanners. In this configuration, the detector's field of view is mechanically deflected (usually by mirrors or prisms) along a preestablished repetitive pattern.

The infrared signal variations occurring along this path produce at the detector's output a modulated electrical signal that can be processed by conventional means to generate, for instance, a visual display representing the distribution of infrared radiation at each point of the field of view being scanned. the instruments of this class are commonly called "infrared cameras." A better designation would be "infrared-to-visible image converters."

INFRARED DETECTORS

The transducers capable of turning the infrared radiation into an electrical signal are called infrared detectors. They are divided into several groups according to their principle of operation, as follows:

Bolometers

The operation of bolometers is based on the measurement of an electrical characteristic variation induced by the heat absorbed by a temperature-dependent element. The metal bolometer is based on a positive conductance variation, the thermistor bolometer on a negative conductance variation, the ferroelectric bolometer and also the pyroelectric detector on a dielectric constant variation. Their response time is around 1/100 of a second, with 1/1000 of a second as a typical upper limit of response.

Photocells

When infrared radiation impinges on these semiconductor devices, electrons spinning in the outer orbits of the detector's atoms can "capture" those photons that have a compatible energy content. If the so added amount of energy is sufficient to allow escape from its orbit and will become a free charge carrier, which will immediately begin to move along the lines of the prevalent electromagnetic field towards the positive terminal of the detector. An electrical current flow is thus generated whose magnitude is directly related to the number of electrons "liberated" by the impinging photons.

However, should the energy added by the photons not be sufficient to "liberate" the electrons, the latter will merely spin faster in their orbit, thus increasing the kinetic energy content of the atoms and, consequently, their temperature. On the other hand, if the photons' energy content is excessive, they will escape capture by the electrons, so no electrical or thermal effect will be apparent at the detector terminals.

This is why the photocells, according to their composition, can only operate as photon detectors in limited areas of the infrared spectrum, that is, only in those areas in which the photons of the radiation possess the "right" amount of energy - just enough to liberate electrons that, according to the characteristics to the associated electrical circuitry, can:

1. become available as current carriers, thus decreasing the dc resistance of the semiconductor;
2. accumulate at the opposite sides of a self-generated potential barrier, thus developing a voltage difference across it; and
3. move in opposite directions because of external magnetic field, thus again generating a voltage across the semiconductor.

Case 1 deals with a conductivity effect, and the detectors of this class are called photoconductive. In case 2, there are the photovoltaic detectors. In case 3, there are the photoelectromagnetic detectors.

The time response of these photon detectors is on the order of microseconds or less, which is about three orders of magnitude faster than the thermal detectors and, of course, is independent from their physical mass, since no thermal effect is involved.

The infrared detectors used in fiber optics radiometric systems are mostly of the photon-detector type. their choice is dictated by the thermal range they must cover and by the response speed required. Lead-sulfide (PbS) cells operating in the photoconductive or photovoltaic mode. Since the transmissivity of optical fibers is limited to the near-infrared region of the spectrum, the detectors used in these systems do not need to be cooled. Figure 16 shows the response curves of several detectors that can operate at ambient temperature in conjunction with fiber optics. This chart plots D* (a figure of merit related to the detector sensitivity) versus wavelength. As mentioned before, the photon detectors cover just a limited spectral area, while the bolometers and the thermocouples have a flat response throughout the whole infrared spectrum.

THE REFERENCE BLACKBODY

All the infrared radiometric systems equipped with fiber optics are using the ambient temperature as their reference. For those based on ac operation, the chopper's blades are supplying a blackbody signal to the detector in the time interval during which they interrupt the flow of radiation transmitted by the optical fibers.

For systems based on dc operation, the detector must be "zeroed" from time to time to avoid drift problems. Zeroing can be achieved either manually or automatically by instantaneously closing a shutter in front of the detector to establish a ground floor level against which to measure the radiation signal from the target.

THE COOLING SYSTEM

As mentioned previously, no cooling is needed for the detectors matching the fiber optics spectral transmission area. However, since detector performance characteristics vary with its temperature constant or to compensate for the change of its electrical response whenever its temperature changes.

This is achieved by varying the gain of the detector output according to its temperature variation. One or more thermistors are used for this compensation.

SIGNAL PROCESSING

The electrical signal supplied by the detector is of analog nature. It is correlated with the infrared signal impinging from the target according to a nonlinear function. It is of very small magnitude, usually just below the millivolt level. According to how we want to use it, it must be amplified and recorded. Whenever a feedback function is required, dc voltages must be made available at the output terminals.

The basic block diagram depicting the signal flow was shown in Figure 16, in which the elements drawn with solid lines are essential and those with dotted lines are optional. Figure 17 is the picture of a basic industrial fiber optics radiometric system, Thermal Monitor. It consists of three separate subassemblies: the optical fiber bundle, the infrared detector head and the signal processing and display console.

The Optical Fiber Assembly

The optical fiber assembly shown in the photograph is 0.5 meters long and its front end termination is protected in a replaceable ceramic sleeve. This makes the front end totally inert to electromagnetic energy fields. Consequently, it can be inserted without any problem between the turns of an induction coil to allow the detector to "see" and measure the temperature of the object being thermally treated inside the coil.

The Detector Head

This contains a chopper, complete with its electrical driving network, an infrared detector whose bias voltage is supplied by the display console and a very low noise preamplifier, whose output is a low-impedance analog signal that can travel along a coaxial cable (up to 100 meters long) to the display console.

The Display Console

This contains a linearizing amplifier that turns the analog exponential detector output into a linear signal directly proportional to temperature. This signal is then converted into digital and displayed on a digital panel meter (DPM) for direct visual readout of the temperature either in *F or *C. A power supply is also contained in the console.

At the back of the console, several outputs are optionally available, such as the raw analog signal prior to linearization, the linearized signal or a dc voltage or current. These functions can then be used for recording and/or for control of a thermal process through the action of relays that will activate or deactivate the necessary functions.

More Complex Systems

These have evolved from the simple unit described above. Figure 18 shows a thermal monitor equipped with a Hi-Lo logic unit where the target must be kept during the manufacturing process. This is achieved through a feedback loop, with a high degree of precision. For instance, in semiconductor epitaxial deposition processes, where the critical temperature to be kept is 1030oC, the upper control limit can be set at 1031oC and the lower control limit at 1029oC.

Besides the Hi-Lo logic, there is an emissivity control, a gain multiplier knob, a jack for attaching a calibrator unit and, of course, a DPM for visual display of the target's temperature.

When the amount of power needed for target energization is large, a proportional controller is used instead of the Hi-Lo logic unit. In this way, the power correction is correlated to the magnitude of the deviation from the optimum level, instead of being an on-off correction.

Multichannel Thermal Monitor System

Figure 19 shows a multichannel thermal monitor system. Every channel with its own optical fiber and its own detector head is plugged into the control console, where according to the option, it can be processed separately all the way to its own output, or can be multiplexed through a time-shared common set of processing electronics. A knob controlling the time-sharing function is available for setting by the operator.

High Speed Thermal Monitor

A high-speed thermal monitor is shown in figure 20. Its three DPMs display the target temperature in three different ways and at different response times, the fastest of which can reach 1 usec. Systems of this family are ideal to control the power of lasers used for metal welding or surface heat treating, since they measure the target temperature exactly at the spot on which the laser beam is made to impinge.

Another version of these systems (Figure 37) is used to measure the temperature of the rotor blades in jet engines and other turbines. In this version, according to the setting of a control switch, a single DPM displays the average temperature of all the blades of the highest temperature of the hottest single blade. With these indications, fuel consumption can be controlled, engine temperature conditions can be observed and a catastrophic failure of the turbine from single-blade overheating can be avoided.

Emissivity-Independent Systems

Emissivity-independent thermal monitors have been mentioned at the end of the section entitled Infrared Radiation, p. 401. Figure 21 shows one such system, whose block diagram is sketched in Figure 22. A key element is the bifurcated optical fiber, which can, according to the option, be made of different detectors are used. When the emissivity characteristics of the target are those of a graybody, these systems will indicate the target's true temperature no matter what its surface emissivity is. Thanks to the fibers' large numerical aperture, temperatures as low as 200oC can be measured with 1% accuracy.

APPLICATIONS

We have already listed, in the section entitled Advantages and Disadvantages of Fiber Optics, p. 412, the major advantages offered by optical fibers when compared with conventional optics in infrared radiometric systems. Consequently, in a host of applications in which temperature is a critical factor, it is now possible to make temperature measurements precisely where none was formerly possible, and to improve the accuracy of those measurements that until now were carried out with difficulty and lack of precision.

The main areas in which infrared fiber optics instrumentation is used to resolve difficult problems of temperature monitoring and control in industrial processes are the following:

Metal Production

Melting, continuous casting (Figure 23), annealing (Figure 24), galvanizing, roll-milling (Figure 25), etc. - in all these applications, the detector "watches" the target through smoke, fumes, vapors, water and even solid walls, thanks to the shielded path of constant transmissivity offered by the optical fibers.

Metal Induction Heating

Because of the strong RF inductive energy field needed to heat the metal parts to be treated, conventional temperature-measuring devices are useless because they will be heated directly by the induction field.

Figure 26 and 27 show two typical applications of fiber optic systems to monitor and control induction treatment of metal objects either stationary in, or moving through, induction furnaces.

Precise control of the temperature needed for perfect heat treatment of metal parts (bolts, cam shafts, axles, gears, etc.) is essential to produce the crystal structure that will ensure meeting or exceeding the mechanical characteristic specifications.

The use of fiber optics infrared control equipment:

- allows the viewing end of the fiber optic to be placed in close proximity of the target;
- saves energy by allowing only the precise amount of power to be used;

- speeds up production by controlling process by temperature instead of time and by allowing faster heat injection rate;
- prevents fiber optics from being affected by the induction energy field; and
- allows electronics to be remoted to radiation-free area.

Metal Forging, Hot Stamping, Pipe Bending

Forging of metal parts includes both rough shape as well as precision forging, which requires less material removal and waste. Pipe bending and shaping is also included in this application. These operations are carried out by heating the parts to be worked on to the optimum temperature with any of the several means available (ovens, flame, induction field, etc.). If the part temperature is below the optimum, cracks and internal tensions will develop, while if it is above the optimum, drooping will take place. The precise temperature control afforded by the use of infrared fiberoptic controllers will:

- avoid the formation of defective parts (from cracks or drooping), thus eliminating rejects and waste due to these defects;
- save thermal energy by ensuring that no heat is wasted by heating the parts beyond the optimum level; and
- speed up production by allowing a faster rate of heating the parts without danger of temperature overshoot.

Metal Casting

The die temperature is of critical importance in die casting of metals. Thermal cycling of aluminum products, with reference to die temperature has been successfully implemented with the help of optical fibers. Figure 28 shows schematically and in detail how the front end of the fiber is inserted through the mold frame and held in a corner of the runner plate, in contact with the aluminum flowing through it.

The major advantages offered by this solution are: (1) substantial savings of thermal energy by eliminating overheating and drastically reducing production rejects; (2) increased production due to the speedup the casting cycle, with the operation automatically controlled by the temperature of the casting material and not solely by time, resulting in faster operation; (3) improvement in the quality of the casting due to control of the process as a function of temperature, resulting in simpler operation and automatic compensation for a cold die startup or interrupted cycles; and (4) direct indication of the die and furnace pot temperature of the metal. Low metal level and blocked water lines are easily indicated several shots before the casting can display conditions visibly.

Saw Production

Teeth hardening, annealing, ends forming and joining (in the case of band saws) are operations in which the optimum crystal structure of the steel is obtained only if the correct temperatures are reached, held and controlled within close tolerance limits. Infrared fiber optics systems used in these applications offer the following advantages:

1. Fast speed of response enables high production quantities to be processed.
2. Fiber optics are small and can get in close proximity of the areas under thermal treatment.
3. Very small spot size of the fiber optic enables focusing individually and sequentially on each and every tooth.

Control of Metal-Working Laser

Lasers, generally high-power CO2 lasers, are used for welding, surface treating and finishing metals of various types. The conventional approach is periodically to sample the beam to keep its power at the desired level. This approach, however, cannot take automatically into account the emissivity variations of the target surface. These variations, in turn, affect the amount of laser power absorbed by the target and, consequently, the target's temperature, which is of paramount importance for the good performance of the operation.

This difficulty is overcome by the use of emissivity-independent infrared fiber optics system (EITM) aimed at the spot of laser beam impact (Figure 29). The infrared system is made blind to the laser wavelength and, in this way, it measures precisely the target temperature at the same spot. Further, via a feedback loop, it controls the laser power to ensure that the operation is carried out at optimum temperature.

Among the advantages offered by the fiber optics infrared approach are the following:

1. It allows noncontact temperature measurement in real time.
2. Fiber optics allow easy access to view the laser heating area because of their relatively small size.
3. EITM compensates for variations in emissivity as the part is being heated.
4. EITM response can be matched to the response speed of the laser.

Fusing Armature Windings in Electric Motors

This operation, better defined as thermocompression bonding, is carried out by near injection and mechanical compression on the point where the wire is looped around the commutator contact hook. Ac current flowing through the heating electrode brings it up to a temperature high enough to vaporize the wire's insulation, but not enough to melt the wire. According to its mechanical configuration, the joint rises to a level between 800oC and 2000oF in a very short time (typically between 50 and 100 usec).

Figure 30 shows an infrared fiber optics system mounted on top of an automatic high-speed machine that sequentially fuses every armature winding to its corresponding hook of the commutator lug. Figure 31 shows a typical electrical motor with the wire-to-hook ends prior to fusing. Note how some of the hooks are still standing up, while others already have been bent down. Figure 32 shows in detail the fusing area, with the electric motor at left and the optical focusing head of the fiber optics in the upper right corner.

Major advantages offered by the fiber optics controller are: (1) increased speed of operation due to the possibility of faster heat injection and faster indexing; (2) elimination of defects from unsoldered, poorly soldered or open joints because of melted wire; and (3) ease of precise aiming at the spot of heat injection.

Crystal Growing

In semiconductor manufacture, silicon and germanium crystals must be grown from their molten state. Similar growth procedure applies for the crystals used for lasers. In all these operations the perfect lattice structure of the crystal is of paramount importance. The temperature of the meniscus between the molten material and the emerging crystal is the element controlling the diameter of the "carrot." The heat necessary to keep the molten material at optimum temperature is supplied by an RF energy field. This prevents the use of conventional temperature-measuring devices and even the proximity of infrared detectors.

The use of fiber optics infrared control equipment (Figure 33) solves the problem and offers the following advantages:

1. Fiber optics can be inserted inside the system and focused on the meniscus while the detector can be placed outside the energy field;
2. If other than normal atmosphere is present, fiber optics can be sealed into the meniscus by the detector allows precise control of its temperature through a feedback loop acting directly on the induction energy field.

Semiconductor Epitaxial Deposition, Doping, Sputtering

Semiconductor wafer induction heating for doping, epitaxial deposition, sputtering, etc., is generally carried out in hermetically sealed quartz vessels, where vacuum or precisely controlled gas atmospheres are present. Precise temperature monitoring devices can possibly be used.

The use of fiber optics infrared monitoring and control equipment (Figure 34) solves the problem and offers the following advantages:

1. Fiber optics enable noncontact measurement of temperature.
2. Fiber optics can reach inside a hermetically sealed vessel and carry the radiation signal from the wafers to the remotely located detector head and electronics.
3. Thermal process can be automatically carried out within preset optimal temperature limits.

Furthermore, the optical fiber can be manually scanned along the length of the induction oven to determine its thermal profile and to eliminate temperature gradients by adjusting the spacing between the turns of the induction coil.

Semiconductor Eutectic Chip Bonding

Gold-silicon eutectic makes the most reliable chip-to-substrate bond in seamy-conductor manufacturing. However, temperature control of the process is quite critical. The eutectic flows at 385oC and the tolerance is -0o + 20oC. Outside said tolerances the chip might be just "tacked" or sitting above voids, or, at the high end, the gold would begin alloying into the silicon and spoil the doping.

A very thin optical fiber threaded through the collet allows the infrared detector to "see" the chip during the bonding operation. At the instant when the eutectic flows, a large increment of the infrared radiation emitted by the chip's upper surface signals that the optimum temperature has been reached and, through a feedback loop, the process is terminated.

Advantages offered by the fiber optics infrared approach are as follows:

1. Fiber optics can be threaded into the collet in a permanent, unobtrusive setup.
2. Real-time response enables precise control of the bonding process by signaling the precise time when scrubbing must start and when a good bond is made.
3. High speed of operation allows faster rate of heat transfer from substrate to chip.
4. It ensures reliable bonds of semiconductor chips to substrate.
5. It eliminates the high-skill operator requirements and allows fully automated mass production.

Figure 35 shows the detail of a typical fiber installation in the collet of a eutectic chip bonder.

Polymer Extrusion and Injection

Precise and control of melt temperature is essential to ensure optimum length of the polymer molecule and consequently, to maximize the physical properties of the product. Until now, thermocouples have been used to obtain an indication of the polymer temperature, but with the large errors due to the heat from the friction of the polymer against the thermocouple's protective capsule and the latter's thermal connection to the heated barrel. To accurately measure the melt temperature, a fiber optic probe with a high-pressure window is inserted into the barrel flush with its inside wall, so that it will measure only the temperature of the polymer flowing in front of it. If the melt temperature is at least 10% higher than the barrel's temperature, a standard polymer probe can be used. If the melt temperature is equal to, or lower than, the barrel's temperature, an air-cooled polymer probe must be used.

Advantages of the fiber optics infrared approach, which is shown schematically Figure 36 are as follows:

1. Melt temperature measurements are accurate.
2. The response is 1000 times faster than thermocouples.
3. Since polymers are partially transparent in the infrared spectrum, the system measures average temperature to a depth between 5 and 20 mm into the melt, thereby avoiding errors caused by the barrel's temperature effect on the interface between the melt and the barrel.
4. A feedback loop ensures automatic temperature control within narrow tolerances.

Plastic Castings Ejection

Plastic material injected into molds must be ejected during its colddown process as soon as it has solidified to the desired hardness. This is achieved by special "ejector pins" equipped with optical fibers lined along their core. Through these an infrared detector can "see' the plastic material injected into the mold. Thanks to the partial infrared transparency of the plastic, the radiation reaching the detector carries thermal information not only from the area contacting the fibers, but also from a certain depth within the plastic material (approximately between 5 and 20 mm).

Advantages offered by fiber optics infrared controllers are as follows:

1. There is real-time temperature measurement in depth.
2. The high speed response enables material ejection at the precise moment of cooling.
3. Fiber optics are not affected by mold temperature.
4. They compensate for wrong temperature of the molds.

Mold Temperature Monitoring in Glass Production

The temperature of the mold into which the glass is blown is of critical importance because of the following:

1. If the mold is too hot and is opened by the time sequence, the glass just molded will not have developed hard skin and will sag.
2. If the mold is too cold, the glass will have stresses, causing it to shatter.
3. If the mold is too cold, the glass will tend to harden too quickly, thereby resulting in voids in the product.

By use of a fiber optic thermal monitor controller, the fiber optics can be focused on the inside surface of the mold that comes in contact with the molten glass during the time interval when the mold is open. The advantages of fiber optics are: (1) easy placement of the fiber optic to view the inside of the mold; and (2) long length of fiber to keep the infrared detector away from the heat of the molds.

Turbine Blade Temperature Monitoring (Figure 37)

During operation, the blades of the turbine rotors must be kept cooled constantly by circulating air through special channels located inside each blade. In the event that in one or more blades those channels should become blocked, overheating of said blades would develop, possibly reaching the softening temperature of the steel of which they are made. At this point, centrifugal force would produce deformations that could cause quick destruction of the turbine.

Optical fibers introduced through the outside "skin" of the turbine at a convenient location and with the necessary orientation will allow an infrared detector to "see" the rotor blades as they traverse, one by one, its field of view (Figure 38). In this way, thanks to its microsecond response time, the detector will be able to precisely measure the temperature of each and every balde.

In the event that even a single blade should exceed a preestablished temperature safety threshold, an alarm signal will appear at the system's output, and a feedback loop could automatically throttle down the turbine and avoid a catastrophic failure.

Spot Welding

Until now, spot welding operations were controlled by adjusting or setting pressure time, voltage and current. However, the key parameter, temperature, could not be measured because the metal where the "nuggett" was being formed could not be reached by any temperature-measuring device.

Not any longer. Optical fibers introduced inside one of the welding electrodes are now allowing an infrared detector to "look" at the center of the area where the "nuggett" is being formed. Feedback electronics make instant-by-instant current corrections to ensure that the temperature development of the nuggett matches an optimum thermal profile stored in the controller's memory. In this way, a perfect spot weld is produced every time. Figure 39 is a schematic diagram of such a control system, while Figure 40 shows the welding electrodes detail and the optical fiber insertion in the upper one.

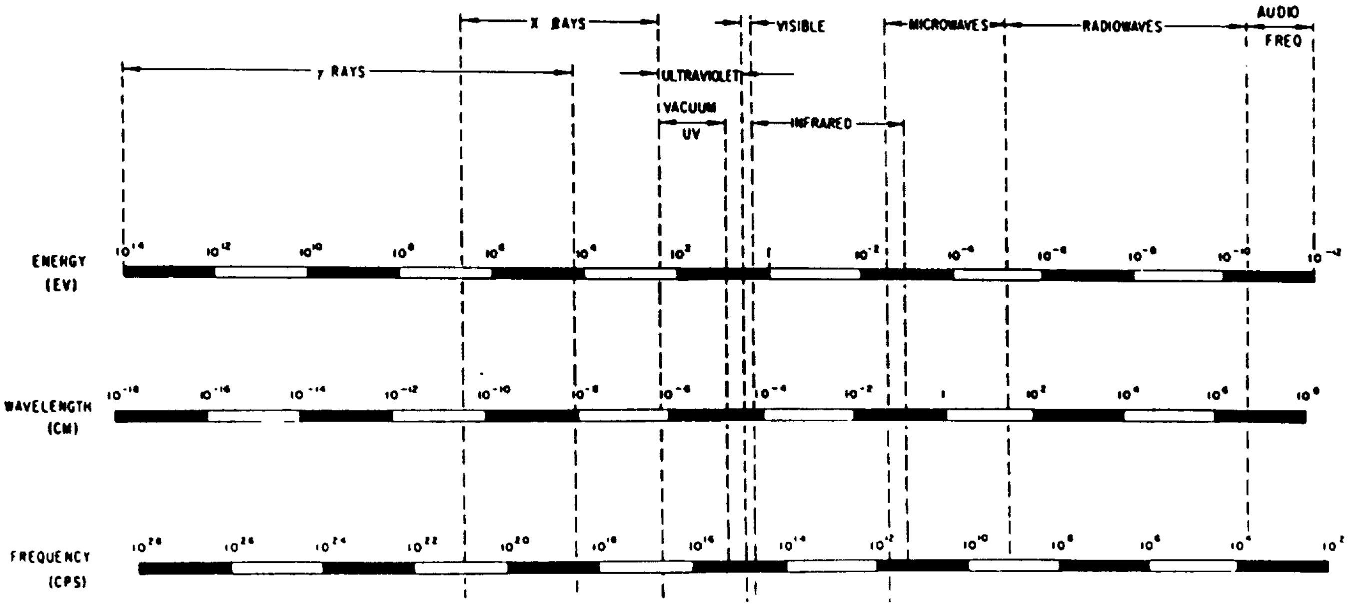

Figure 1. The electromagnetic spectrum.

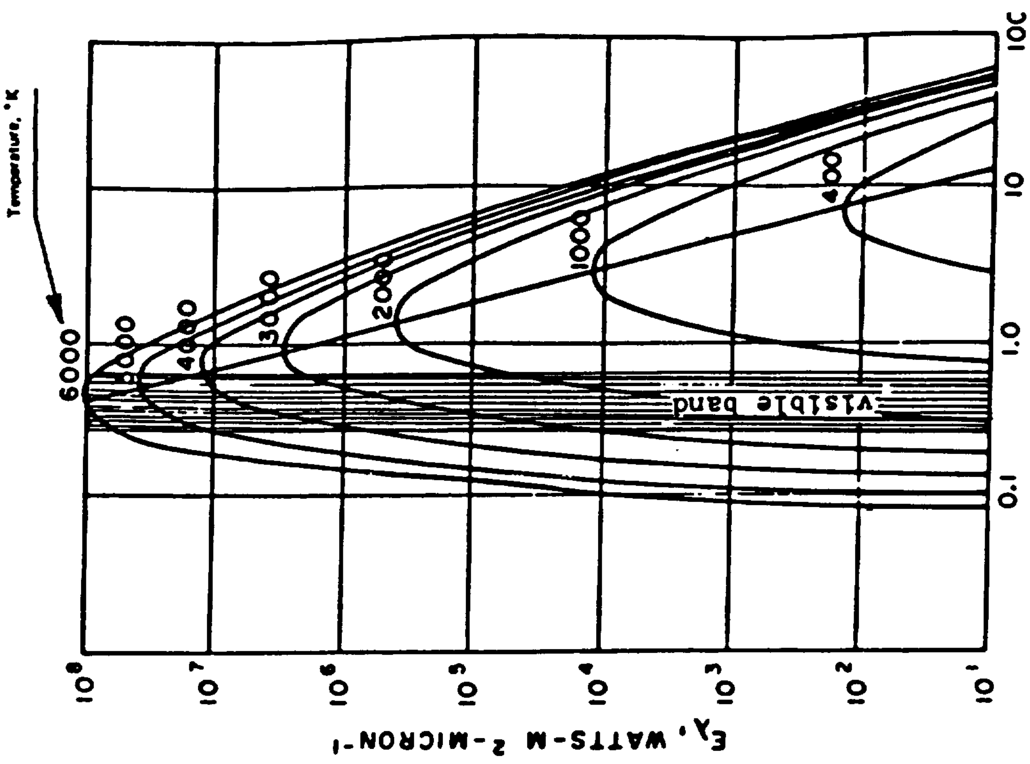

Figure 3. Blackbody radiation curves.

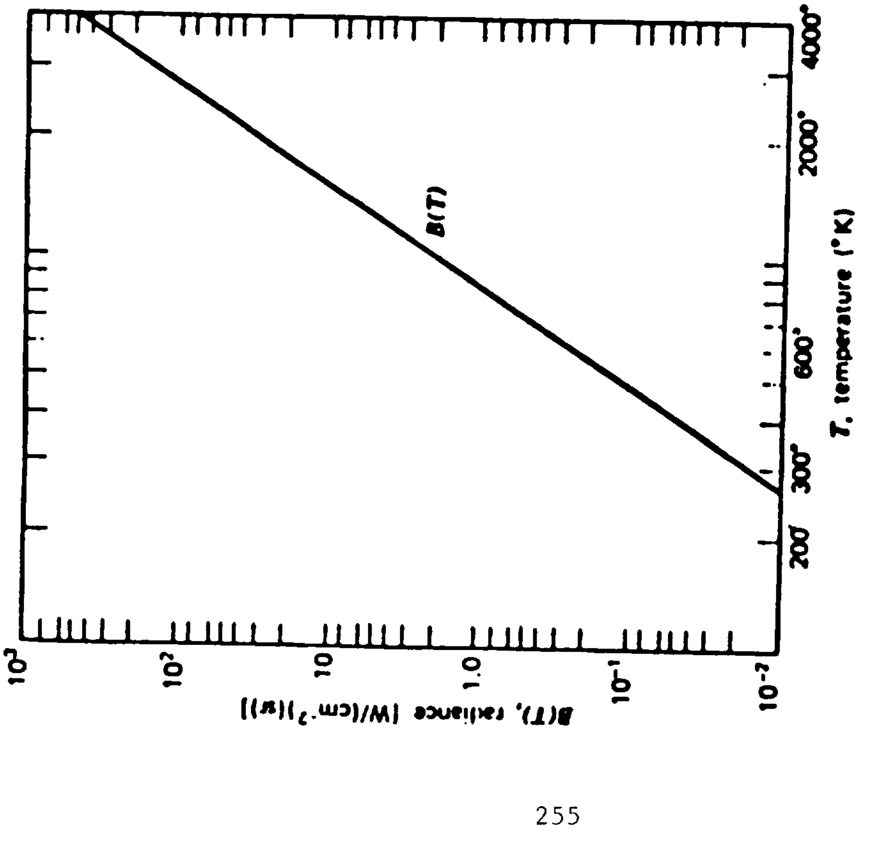

Figure 2. Stefan-Boltzmann law.

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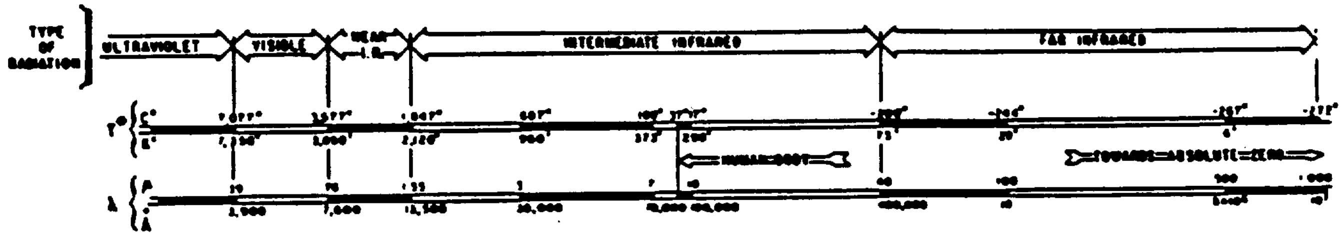
THE 0.1μ TO 1,000μ RADIATION BAND

Figure 4. T° and peak wavelength correlation.

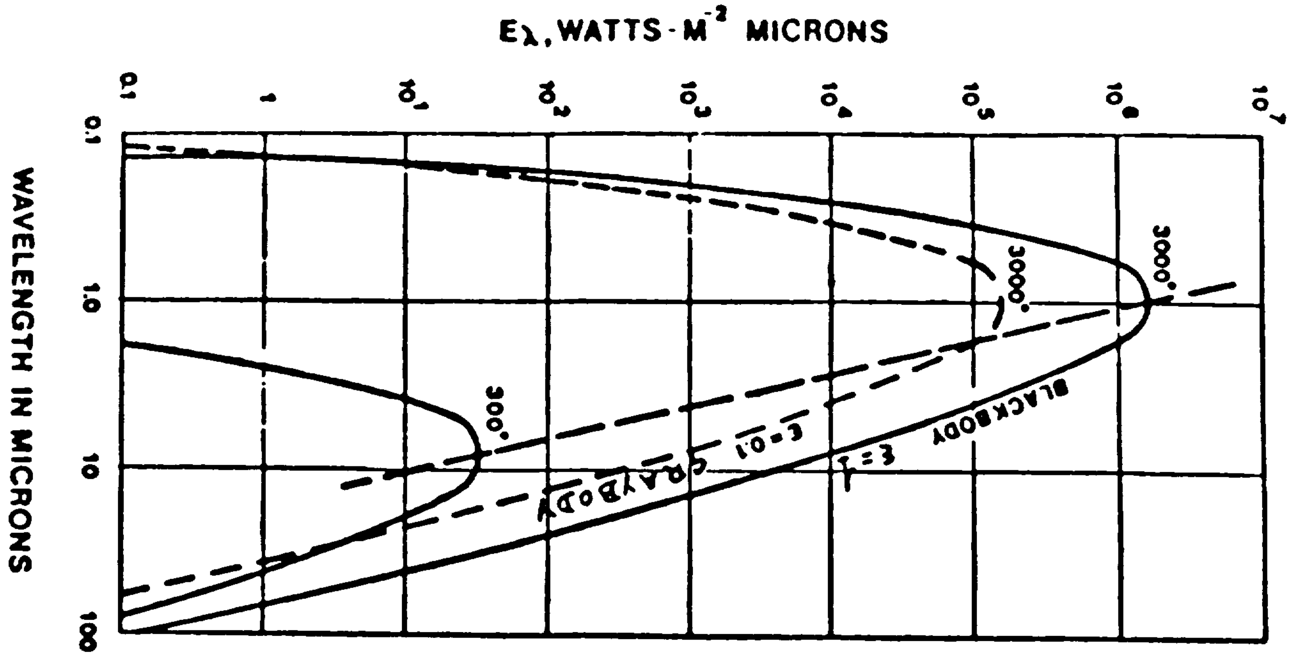

Figure 5. Blackbody and graybody curves.

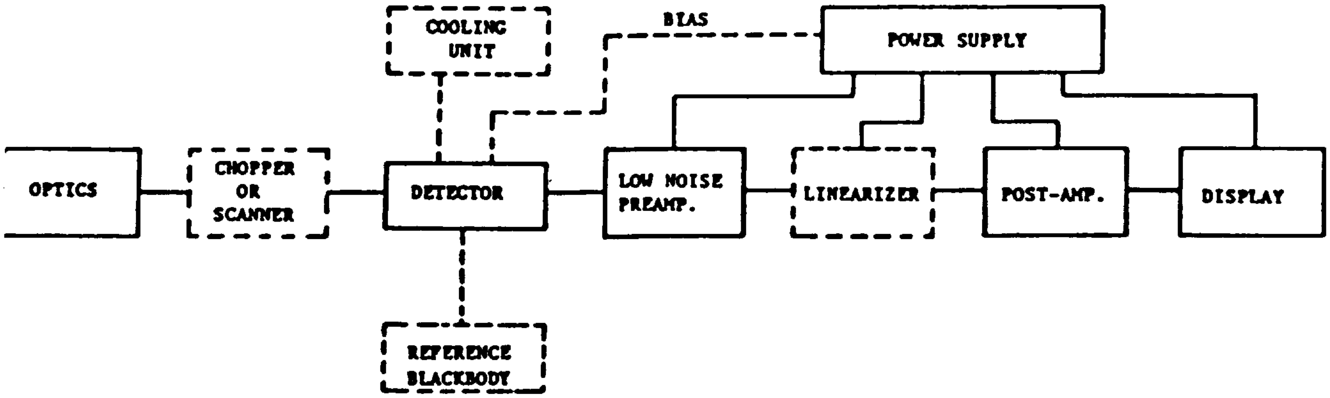

Figure 6. Basic block diagram of a radiometer.

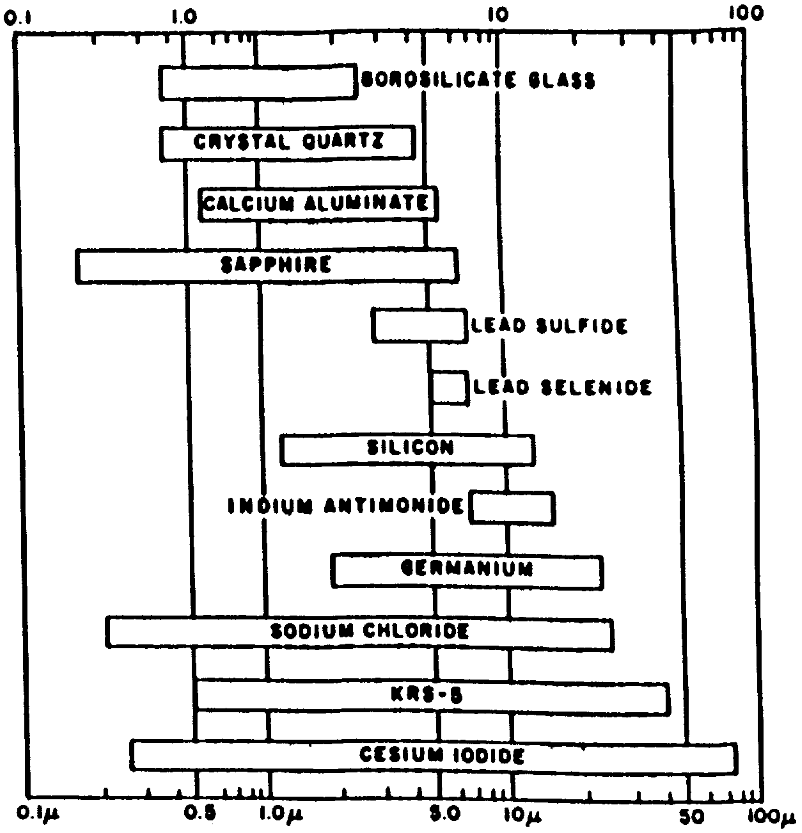

Figure 7. Transmission "windows" of selected optical materials.

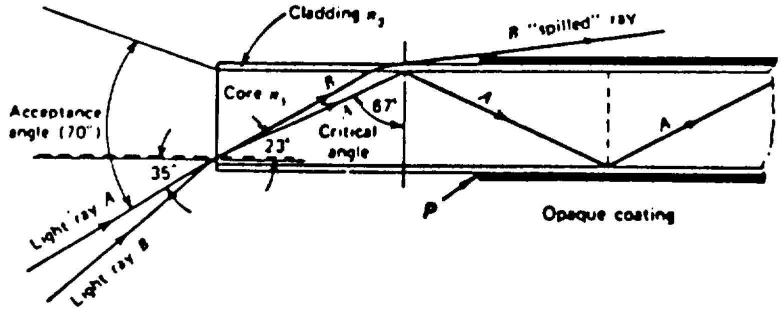

Figure 8. Ray propagation in optical fiber.

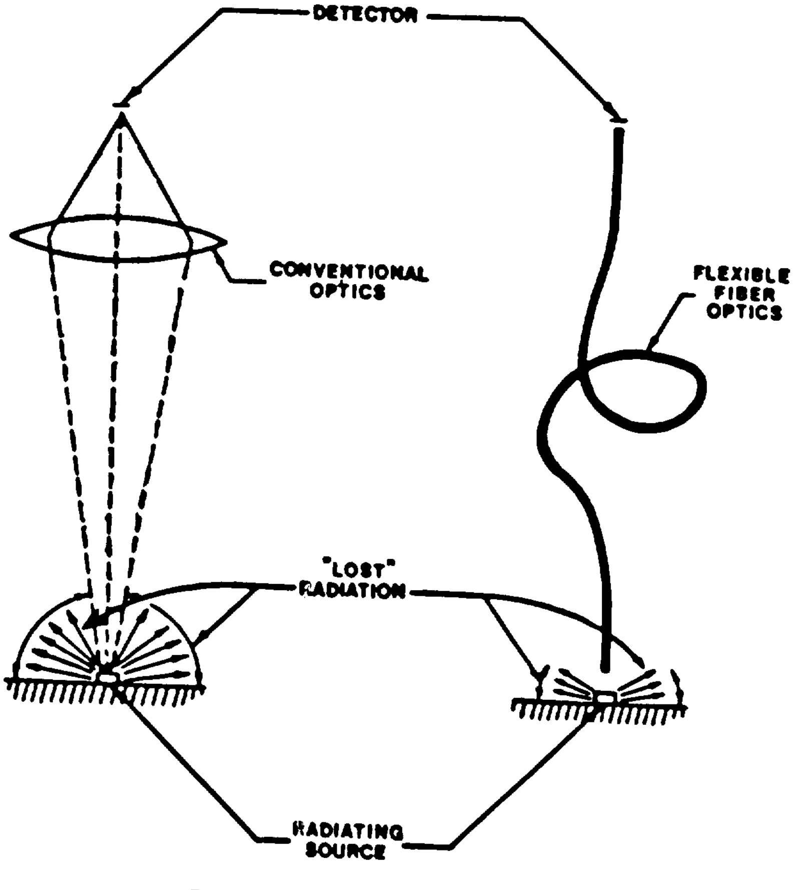

Figure 9. Capture of radiant energy.

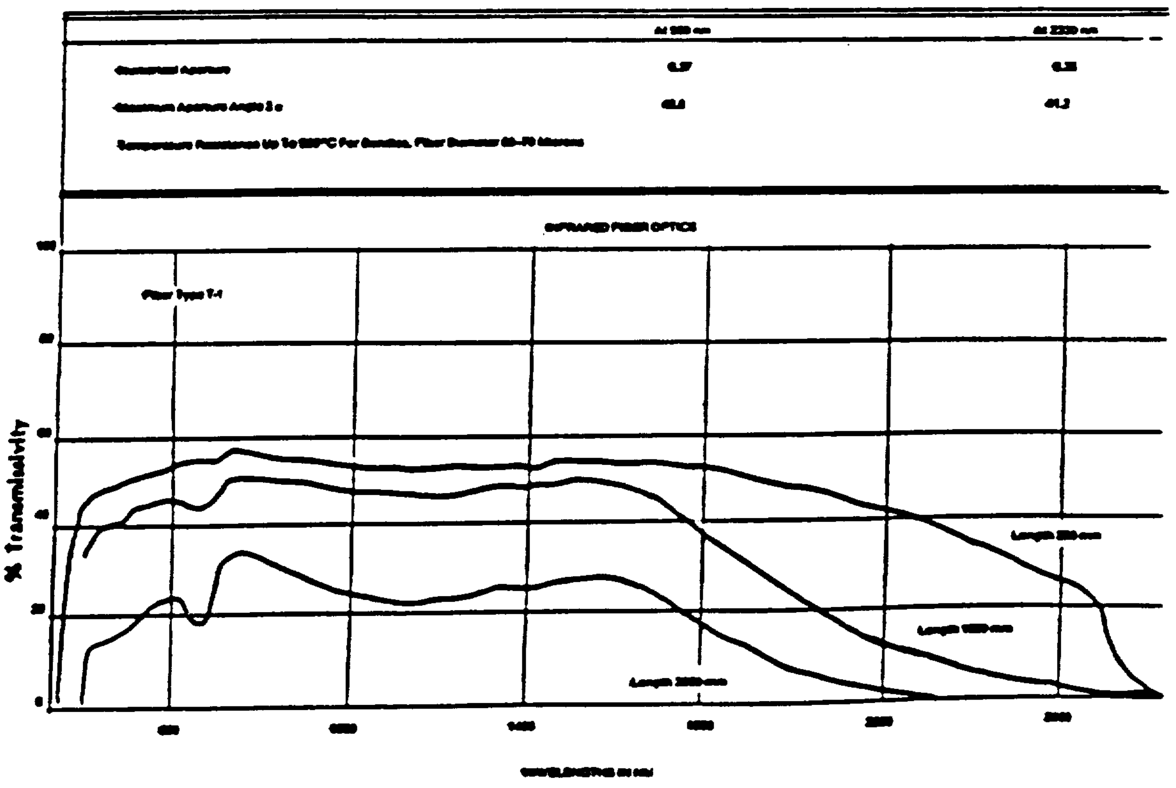

Figure 10. Spectral transmission of infrared fiber optics.

Figure 11. Various fiber optic bundles configurations.

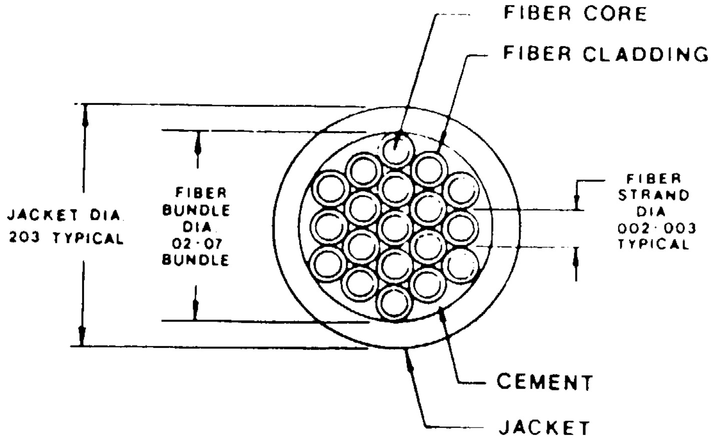

Figure 12. End view of very small fiber bundle.

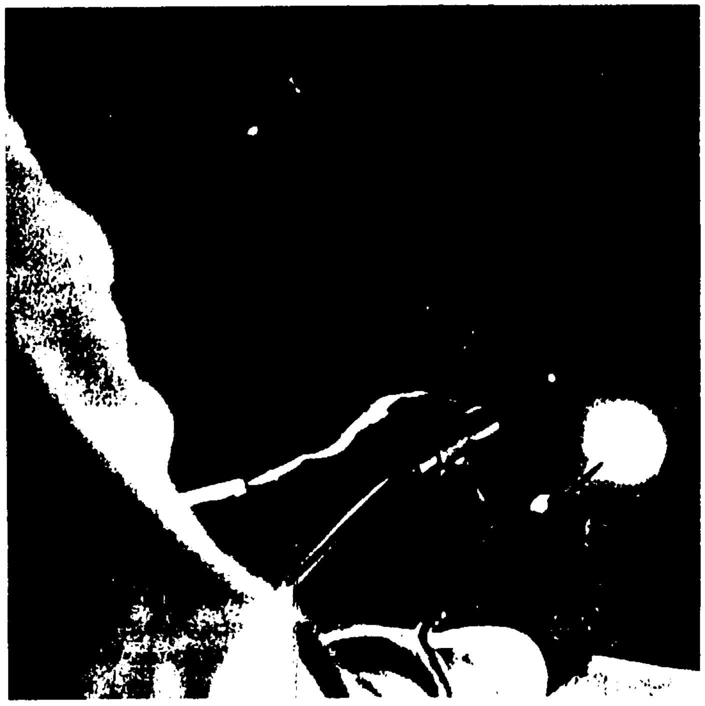

Figure 13. Viewing areas of open and focused fiber optics.

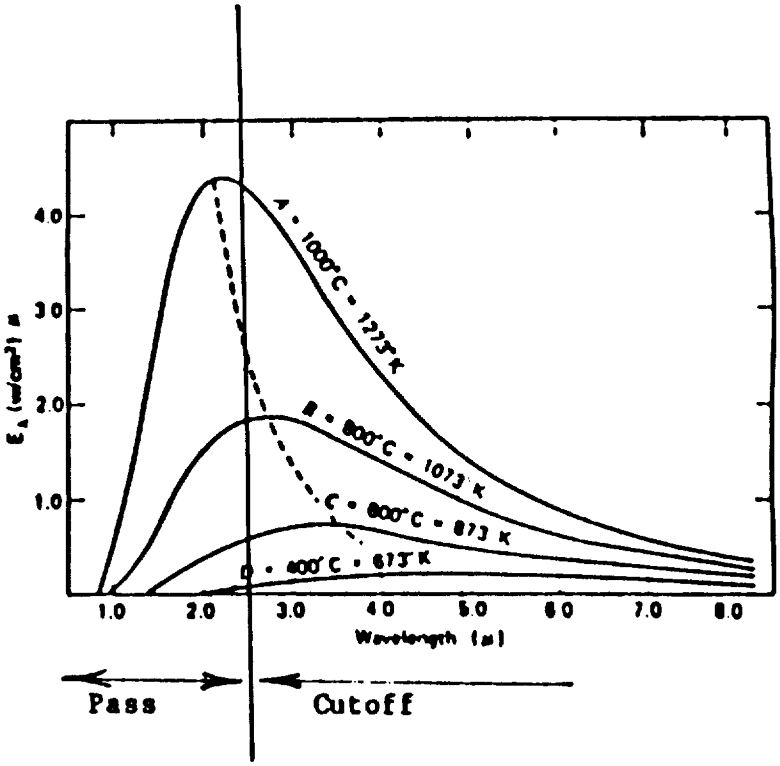

Figure 14. The filtering action of fiber optics.

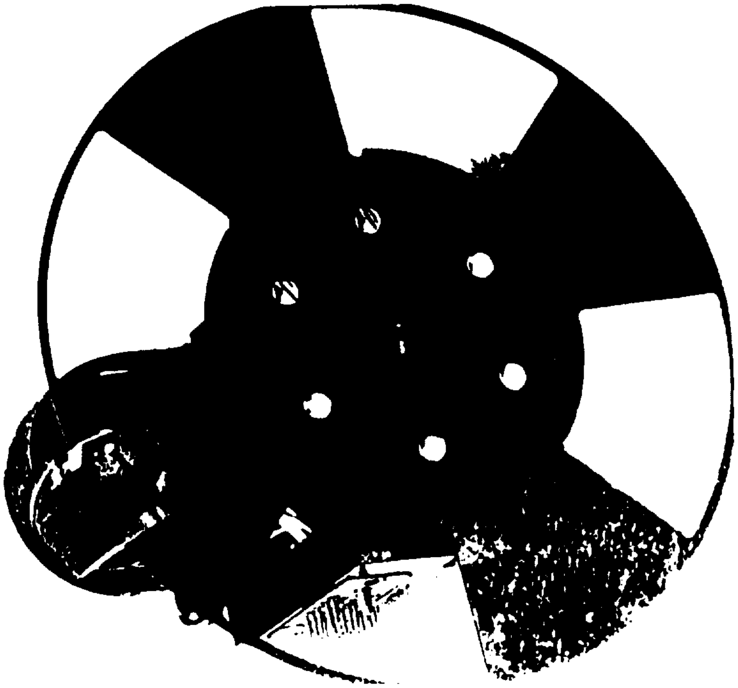

Figure 15. Basic configuration of chopper assembly.

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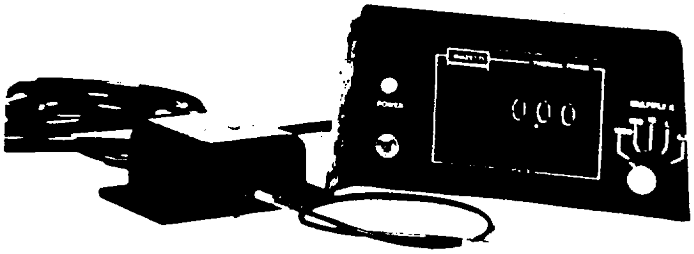
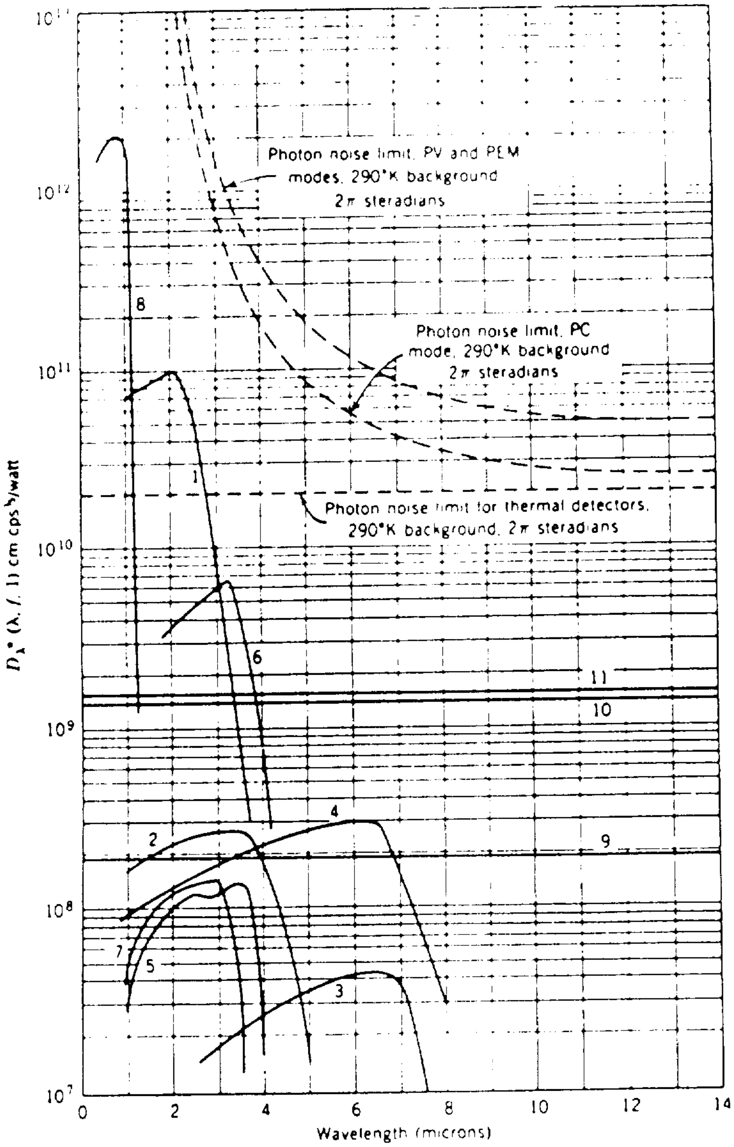


Figure 17. Basic industrial fiber optics radiometer.



(a)

Figure 16. Spectral D_λ^* of room-temperature detectors. (1) PbS, PC (250 usec, 90 cps); (2) PbSe, PC (90 cps); (3) InSb, PC (800 cps); (4) InSb, PEM (400 cps); (5) InAs, PC (90 cps); (6) InAs, PV (frequency unknown, sapphire immersed); (7) InAs, PEM (90 cps); (8) Tl_2S, PC (90 cps); (9) thermistor bolometer (1500 usec, 10 cps); (10) radiation thermocouple (36 msec, 5 cps); (11) Golay cell (20 msec, 10 cps).

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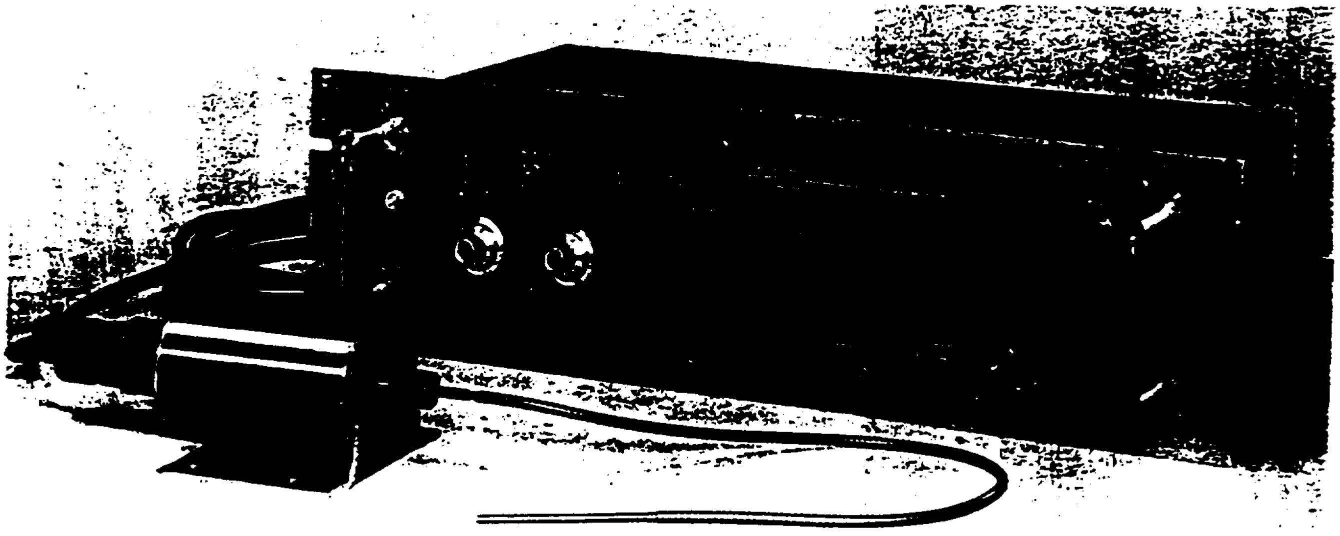

Figure 18. Hi-Lo thermal band controller.

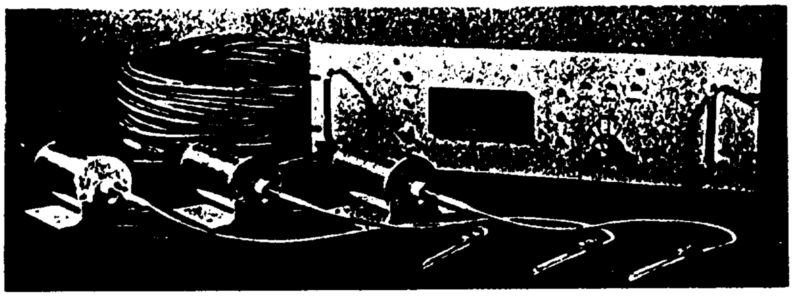

Figure 19. Multichannel multiplexing thermal monitor.

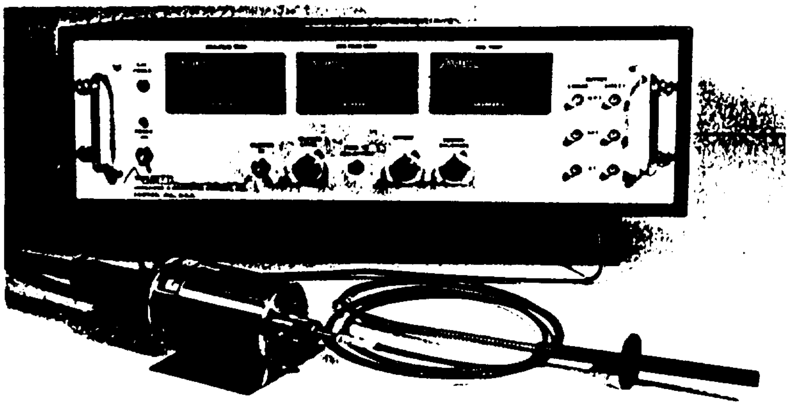

Figure 20. High-speed thermal monitor.

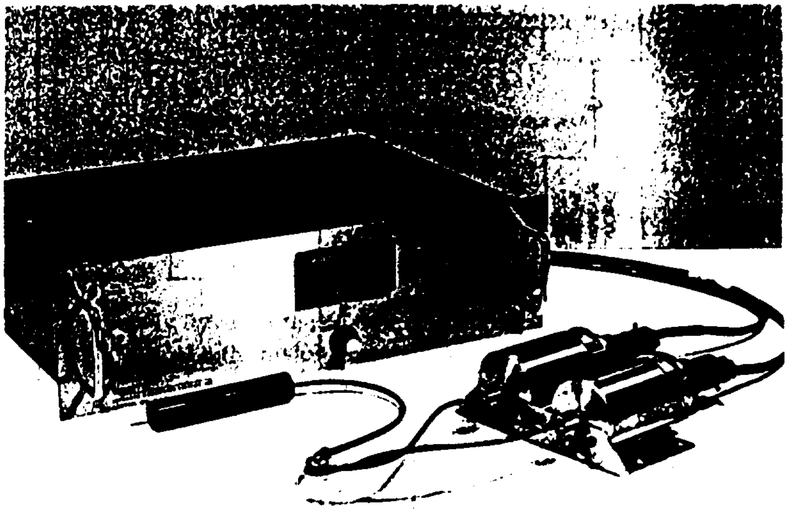

Figure 21. Emissivity-independent thermal monitor.

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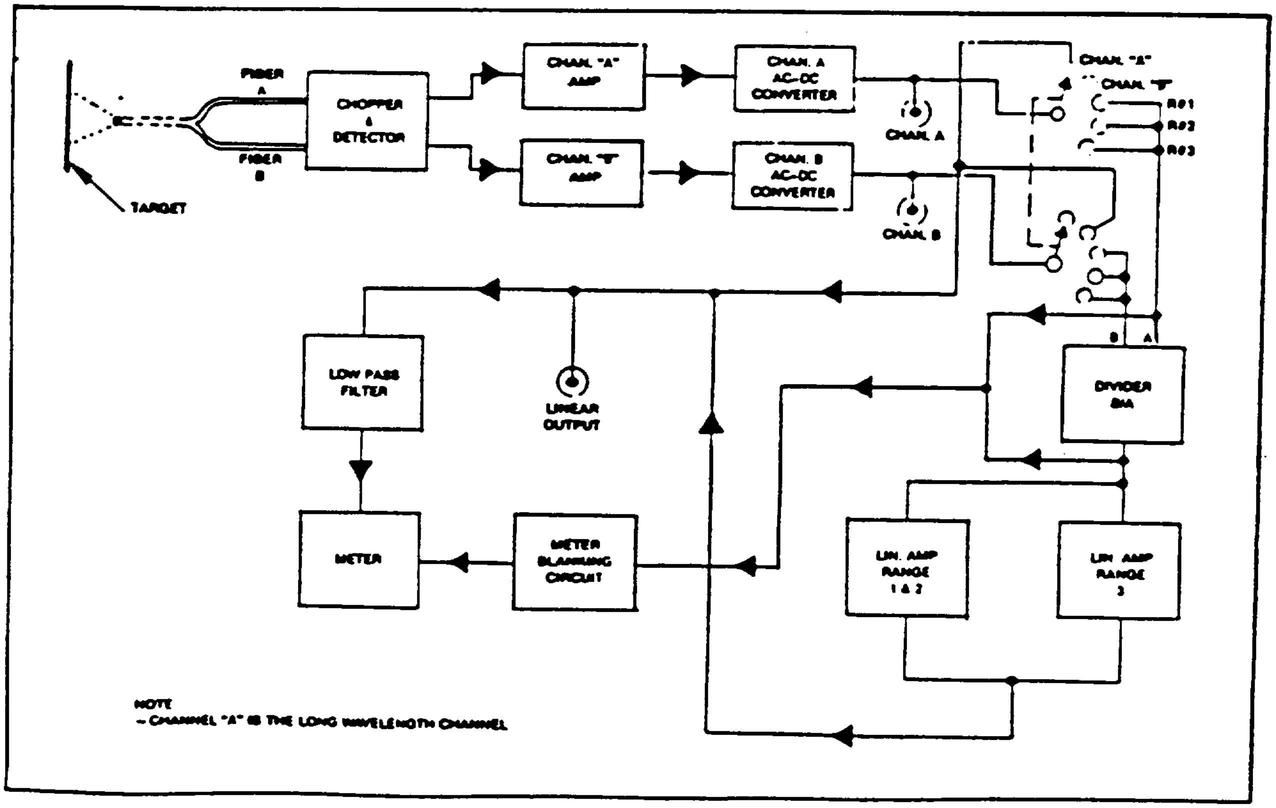

Figure 22. Block diagram of emissivity-independent thermal monitor.

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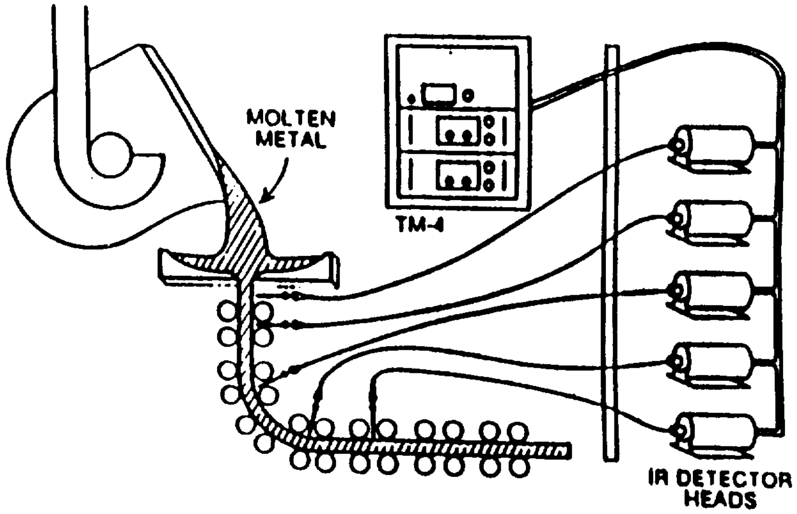

Figure 23. Continuous casting processes.

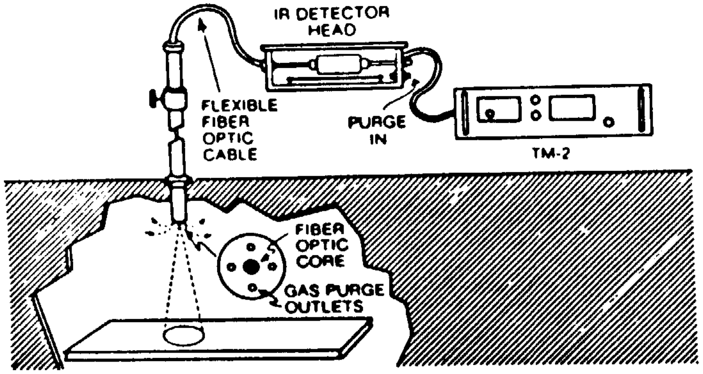

Figure 24. Annealing/heat treating processes.

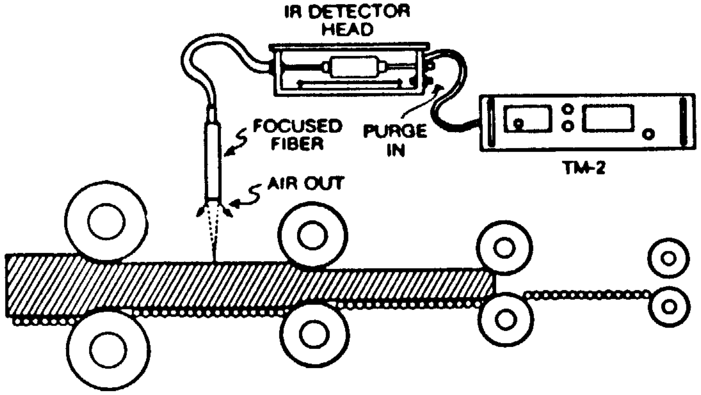

Figure 25. Roll-milling of metals.

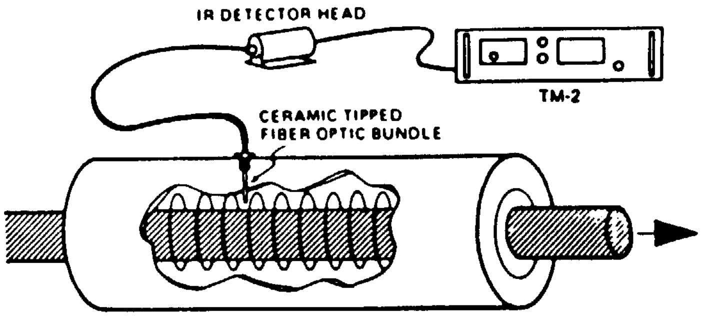

Figure 26. Monitoring steel rod continuous induction heating.

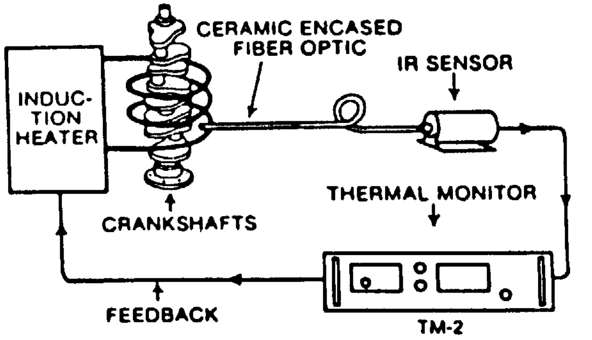

Figure 27. Controlling induction heating of automobile crankshaft.

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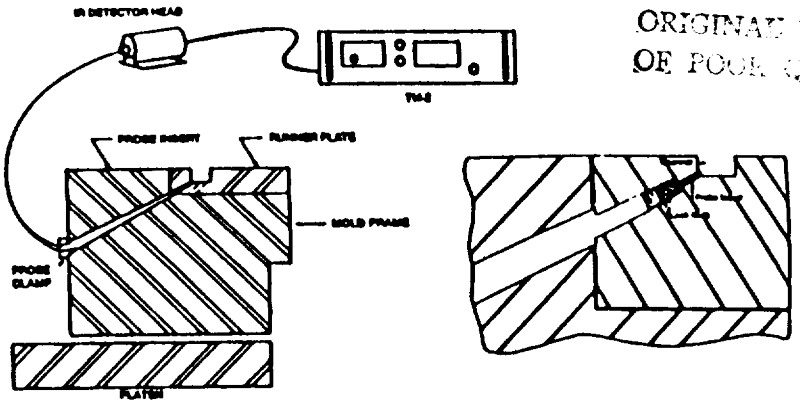

Figure 28. Metal die casting control.

Figure 29. Control of metal-working laser.

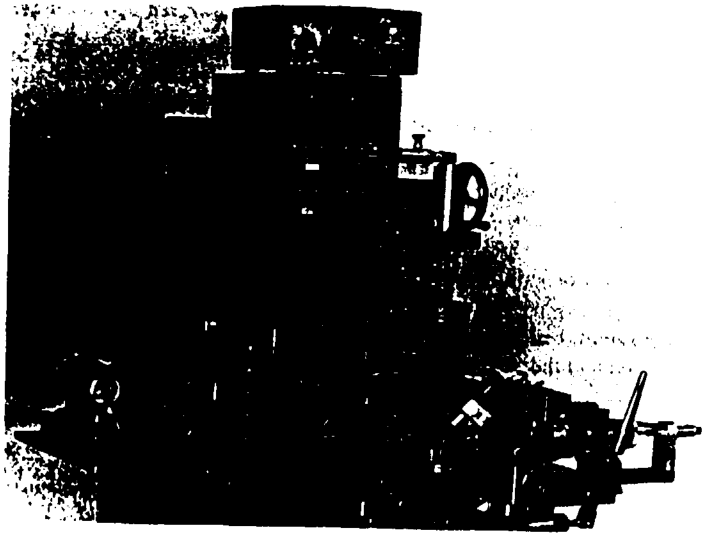

Figure 30. Electric motor commutator fusing machine.

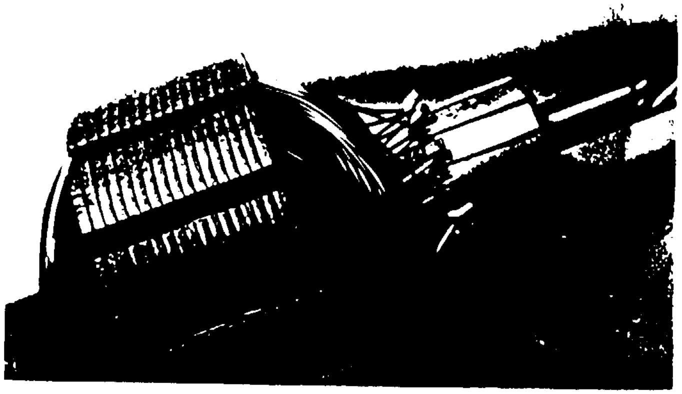

Figure 31. Electric motor prior to commutator fusing.

Figure 32. Detail of fusing area.

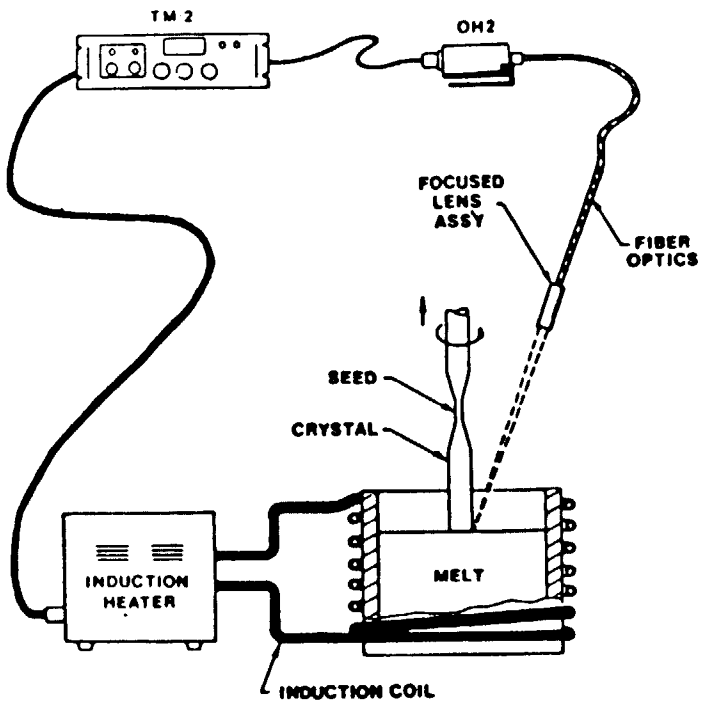

Figure 33. Crystal growth control.

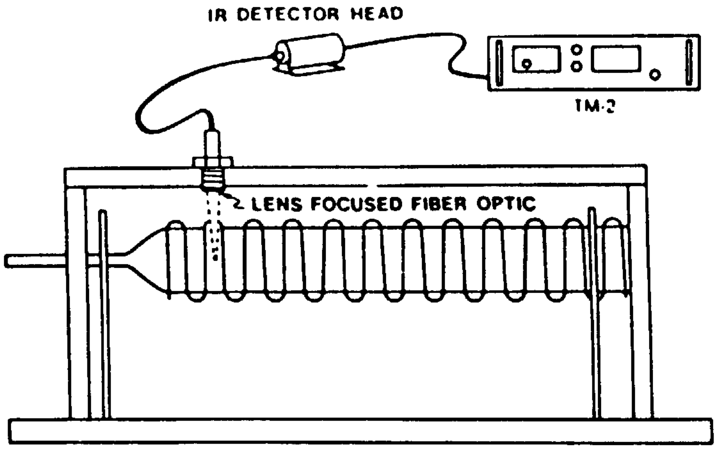

Figure 34. Semiconductor processing inside epitaxial induction oven.

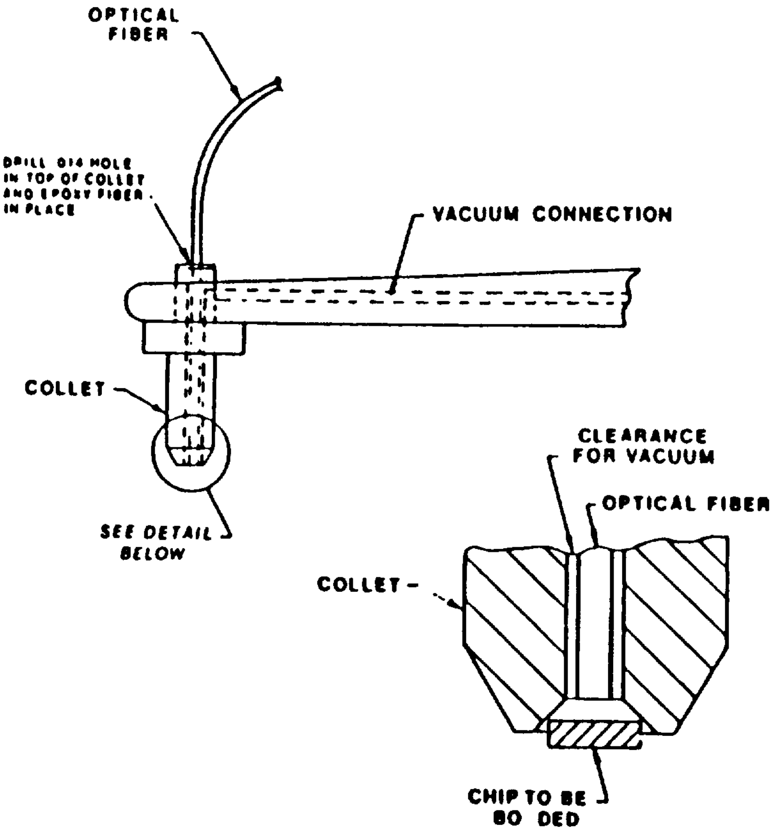

Figure 35. Eutectic bonding of semiconductor chips onto substrate.

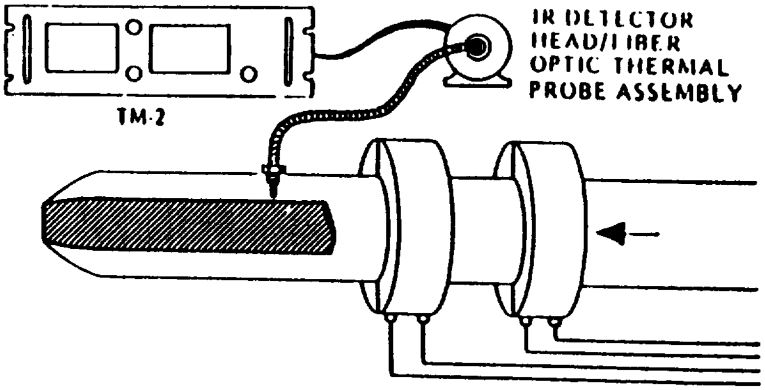

Figure 36. Polymer extrusion and injection.

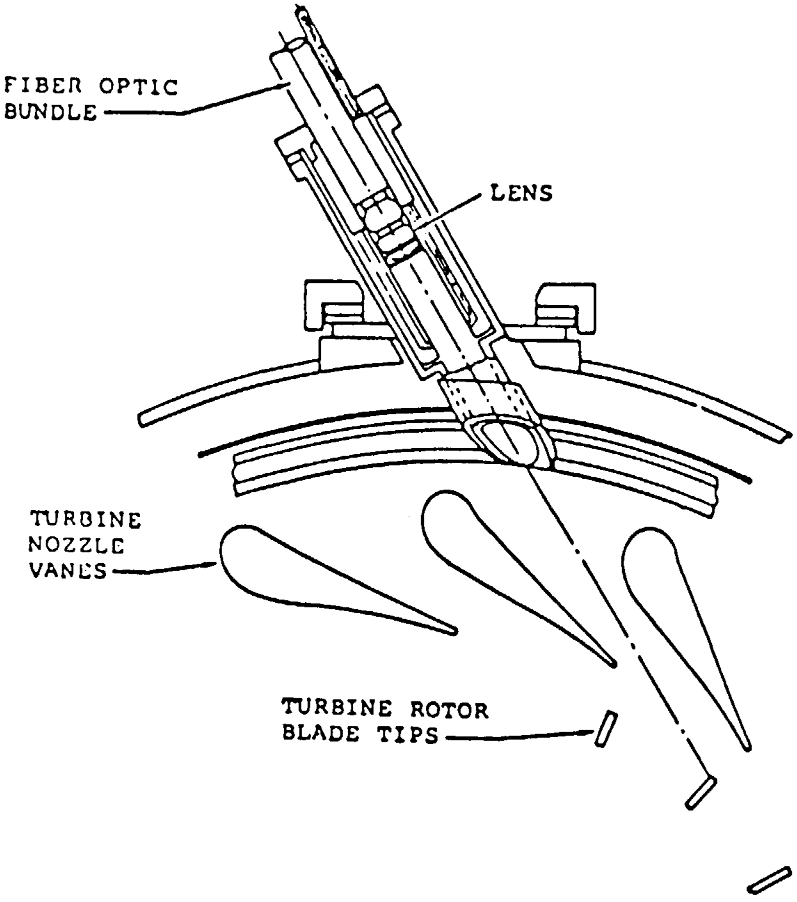

Figure 38. Schematic of fiber optics installation in turbine.

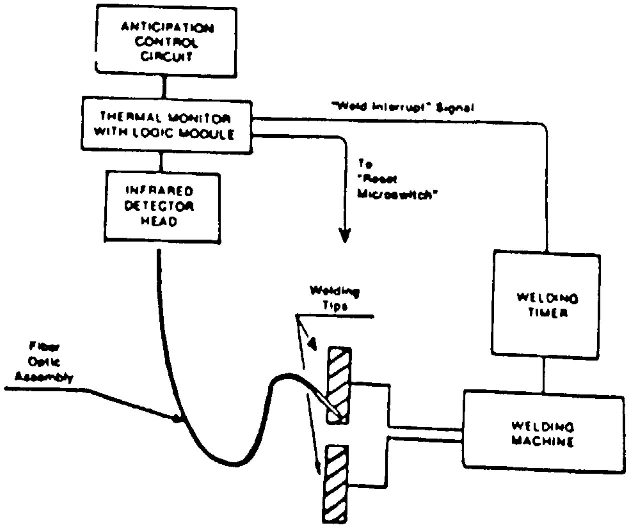

Figure 39. Schematic of spot welder controller.

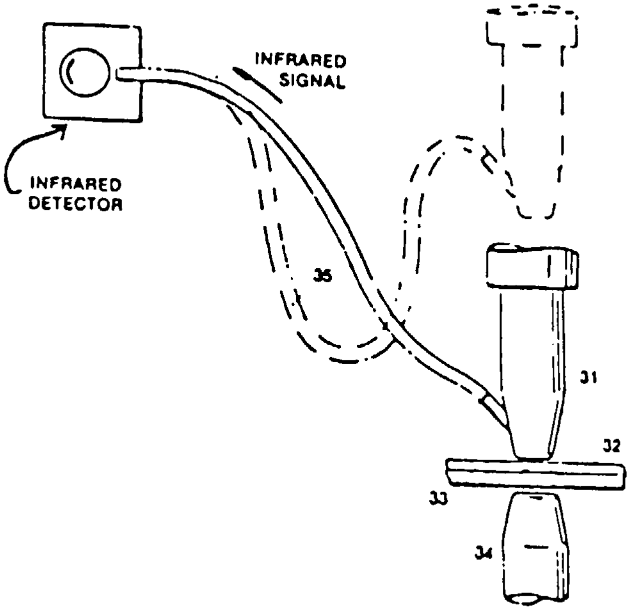

Figure 40. Detail of spot weld electrodes with fiber optics.