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INTEGRATED FIRE AND OVERHEAT DETECTION SYSTEM FOR MANNED FLIGHT VEHICLES

TERRY M. TRUMBLE

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FOREWORD

This report describes research performed by the Fuels, Lubricants, and Hazards Branch, Support Technology Division of the Air Force Aero Propulsion Laboratory under Project 6075, "Aerospace Vehicle Hazard Protection," Task 607501, "Fire Overheat and Explosion Detection." The work reported herein occurred between September 1965 and December 1966. Mr. Terry M. Trumble was the project engineer and principal investigator.

The author wishes to acknowledge the contributions made by his technical assistants, Mr. Harold E. Watson, a student from Northwestern University, and Mr. Robert Hoss, a student from the University of Dayton, whose conscientious pursuit of assigned tasks made possible the timely completion of this effort.

This report was submitted by the author in September 1967.

This technical report has been reviewed and is approved.

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Support Technology Division

ABSTRACT

This report describes the design of a computer for use in a unique integrated system for detecting fire and overheat in aircraft engine nacelles. This system uses ultraviolet and infrared sensors for fire detection, continuous elements for overheat detection, and the newly designed microcircuit computer for sensor analysis. The computer, operating in any of five modes — Normal, Emergency, Ultraviolet, Infrared, or Continuous — activates a specially designed alpha-numeric readout.

Computer design criteria are firmly established, and the finalized two-channel, fail-safe, self-checking computer design is described. Boolean equations and a final schematic for the computer are given. Finally, the limitations of applying the computer from both an engineering and a legislative point of view are specified. A final flight-qualified microcircuit computer weighing 6 ounces or less, 1/2" by 2" by 5" in size, and drawing less than 1 watt of power can be built using the basic computer design formulated.

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INTRODUCTION

1. BACKGROUND

One must understand the past history of fire detection in aircraft engine nacelles to fully understand the development of the new concept of integrated fire and overheat detection systems.

Early concepts of fire detection were based upon simple eutectic alloys that melted from the heat of a fire. The lack of reset capability, poor inherent sensitivity, and point sensing instead of volume or area sensing resulted in poor operational systems. These shortcomings gave rise to the development of new sensors: the bimetallic switch and the rate of rise thermocouple. These two devices became the heart of operational systems in the 1950's. During the 1950's, however, a continuous-element overheat sensor capable of much greater coverage than previous sensors was developed. This device, sensitive to heat at all points along its length, was later improved to delineate between fire or overheat by the use of rate of rise discrimination. During this time period, an infrared sensor was also developed, but it was not widely accepted. Although the new sensors had improved performance and capability, they did not solve all of the problems of their predecessors. To correct these deficiences required many refinements to be made to the continuous systems for improved reliability and performance. These improvements lead ultimately to systems in use on most aircraft today.

In August 1964, however, the results of the Fifth Annual Safety Congress provided the impetus for new programs. Representatives from all major operational air commands attended this Congress. After an analysis of fire detection problems, the following specific recommendations were made: expedite improvements in current systems and initiate a program to advance the state of the art in operational fire detection systems. These recommendations resulted from an analysis of statistical data citing failures, false fire warnings, and subsequent precautionary engine shutdown. Shortly thereafter a USAF directed program to correct these deficiencies was initiated. As a result of this direction, three new systems are being developed. They are an ultraviolet fire detection system, a fiber optics detection system, and a continuous-element thermoelectric fire and overheat detection system. These systems are being developed with state-of-the-art sensors and devices, which should improve their overall environmental capabilities and reliability. These systems should be ready for flight use by 1969.

These new systems still follow the same development pattern of their predecessors. This pattern does not provide for the integration of other new expanding technologies from other disciplines into the fire detection field. Thus, if a major innovation in the field of fire detection is to be introduced, fire detection technologies and other previously unused technologies must be used together.

With the implementation of the USAF directed program in 1964, it became evident that little was left to be explored in the development area of a state-of-the-art fire, explosion, and overheat detection system, since all new useful concepts had been exploited thoroughly under this approach. Therefore, an abstract program was undertaken to specifically attack the problem of false fire warnings and no warnings when fire occurs.

2. PURPOSE AND SCOPE OF PROGRAM

The purpose of the program was to develop an aircraft fire and overheat detection system with the lowest possible false alarm rate, the maximum fire and overheat detection capability, and minimum aircraft down time. A mating of computer reliability, redundancy, and fail-safe technology as well as state-of-the-art sensors in a redundant mode was chosen to provide this technology. The purpose of this in-house research clearly became that of selecting the appropriate sensors, effectively using them, designing a fail-safe computer to continuously interrogate them, and finally, designing a readout with equal capability for reliability and maximum information transmission. While this system was being evolved, the requirement for designing the computer became so demanding and important that the basis for this report will be the computer design requirements and secondarily that of other system implementation. Finally, recommendations for both the computer and the total system will be given to show the envelop of the use of this concept.

SECTION II

PRELIMINARY CONSIDERATIONS

1. BASIC PHILOSOPHY FOR SYSTEM DESIGN

To develop an effective detection and analysis concept for manned flight vehicles required many decisions on the overall effectiveness and usefulness to be determined. After talking to pilots and other crew members, we found the basic problem facing the designer of a system was that of reliability. Ultimately, this is reduced to the confidence crew members put in their fire detection systems. When one is exposed continually to false alarms in aircraft, one gradually loses faith in the system. As a result, the crew member conditions himself to false alarms. When an alarm appears, false or not, standard procedures for shutdown are followed, except during critical maneuvers when the pilot is usually forced to abort his mission. This particular problem has caused some detection systems to be considered as more of a nuisance than a help. The removal of a complete system from operational aircraft has followed. It can be assumed from this picture that the adage "some fire detection is better than none at all" is incorrect. It is far better to reduce mission aborts by leaving ou. the nuisance factor. Maximum reliability is, therefore, the primary goal of this effort at the expense of any other factor that would tend to compromise it.

What other factors influence the effectiveness of the detection system according to crew members? After much discussion with crew members, it was discovered that not enough information was made available so that a good judgment of the damage could be made by the pilot. A newly designed readout to reflect an improvement in this problem is required to serve as a guide for future designers.

Reliability and maximum information transmission require that a maximum number of sensors be used and that as many different types as possible be integrated to maximize information. This decision is discussed in Section II 2. The selection of these types of detectors in multiple arrays requires a computer to analyze all the available useful information. The next step is then to select the type of computer. This selection and final design is also based upon the total information that will be relayed to the readouts. The concept of multiplexing to maximize efficiency and reduce size and weight is discussed for future systems.

In summary it can be stated that the theoretical decisions must consider and propitiously affect the reliability, size, weight, effectiveness, and total usefulness of this concept.

Automatic decisions precluding the crew member's intervention must be considered and the information as to the history of the occurrence visually displayed for human evaluation. Thus, low and slow and high performance vehicles alike can have a common mode concept for fire, overheat, and explosion detection involving the maximum in reliability.

2. DETECTOR SELECTION BY CLASS OF HAZARD

A detector should be selected for each class of hazard so that ultimate reliability can be achieved in detecting the specific hazard. Therefore, detectors for fire, overheat, and explosion will be analyzed here. The results will be summarized following this analysis.

a. Fire Detection

The detection of a fire must be based upon those characteristics specifically identified with a fire. This must be done for the most part to the exclusion of the expected background.

For this effort, fire is defined as the combustion process involving fuels, lubricants, and other flammable liquids primarily of the hydrocarbon type. This combustion process is characterized by several different types of detectable phenomena. Primarily, this process is a radiative process giving rise to rotational and vibrational band emission from the many species in the combustion zone. Useful radiation from this process extends from the middle ultraviolet limit at about 200 nanometers throughout the visible and into the infrared region up to about 5.0 microns. This characteristic is detectable by a multitude of detectors, which, unfortunately, are almost all responsive to background radiation. Background radiation takes two forms. The first is blackbody radiation from hot engine nacelles, leading edges, or other equipment subjected to high ambient temperature where the detectors are to be located. The second type of radiative source is the sun, which can only be considered a problem in areas exposed to the external environment through openings.

Hot metallic surfaces, as infrared emitters, are predictable in their wavelength and amount of power emitted. These radiators are especially effective in the infrared region where hydrocarbon combustion process emission lies. The methods most normally suitable to detect a flame by infrared are: spectral filtering by single wavelength and power radiated or by comparison of two wavelengths, by spatial filtering, and by flicker frequency. Of these choices flicker frequency has proved to be the most effective for aircraft applications. The scintillation of a flame causes modulation of its radiative output so that a frequency below 20 CPS is characteristic. With this method, flame radiation can be discriminated from blackbody radiation from a metal and the flame can be detected.

The 20 CPS or less modulation rate of the flame requires a nominal frequency response of an infrared detector. Standard photoconductive cells and photovoltaic cells are most appropriate for this task. Other detection devices such as thermocouples, bimetallic switches, and eutectic alloy devices are not fast acting enough nor are they sensitive primarily to wavelengths of radiation emitted from a flame. Therefore, devices designed specifically for radiation detection, such as silicon photovoltaic or photoconductive cells, have been used.

As seen in Figure 1, the radiation emission of a hydrocarbon in the infrared region is very high. Discrimination in the visible is much more difficult due to the low blackbody equivalent radiation (1920°K), and as such has not generally been used for fire detection. Ultraviolet radiation from 200 to 400 nanometers is also moderately high for hydrocarbon flames. This entire wavelength region, therefore, could tentatively be used for flame detection. The combustion process for a hydrocarbon flame emits typically in the 200-nanometer to 9-micron region. Fire detectors, such as conventional photomultiplier tubes, Geiger Mueller type tubes, and solid-state infrared detectors, have been used with varying degrees of success.

Since blackbody radiators emit very poorly below 300 nanometers, it is effective to use the 200-nanometer to 300-nanometer region for flame detection with little spurious background from man-made sources or hot metallic surfaces. The sun, however, emits at wavelengths between 200 and 300 nanometers above the atmosphere. At an altitude up to 30,000 feet, however, the absorption and scattering of the upper atmosphere effectively reduce this radiation so that little background exists below 285 nanometers (Figure 2). The ultraviolet detector can, therefore, directly detect flames by wavelength alone and in compartments exposed to solar radiation at altitudes up to 32,000 feet. This is reason enough to include this detector technique as a candidate for the integrated detection concept.

Radiative transfer is only one detectable characteristic that has been used effectively for fire detection. The other major technique is convective transfer which is nonspecific as to its source of heat. Thus, a hot compartment, not on fire, could conceivably trip a convective device. Convective devices are typically thermocouples, bimetallic switches, and eutectic semiconductor cables. The bimetallic switches and thermocouples are point-sensing devices and must be carefully placed so that the fire can be detected. A continuous eutectic type is

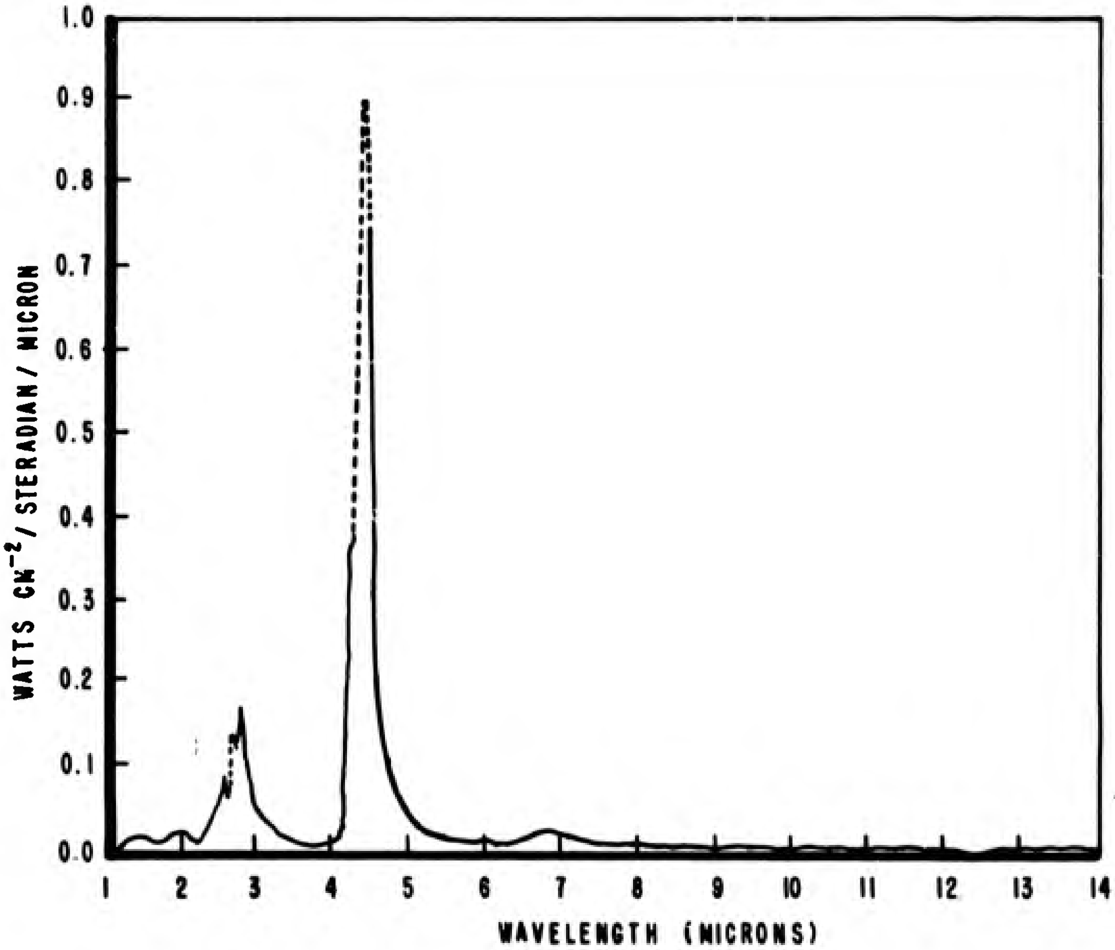

Figure 1. Spectral Radiance of a Typical White Gasoline-Air Flame

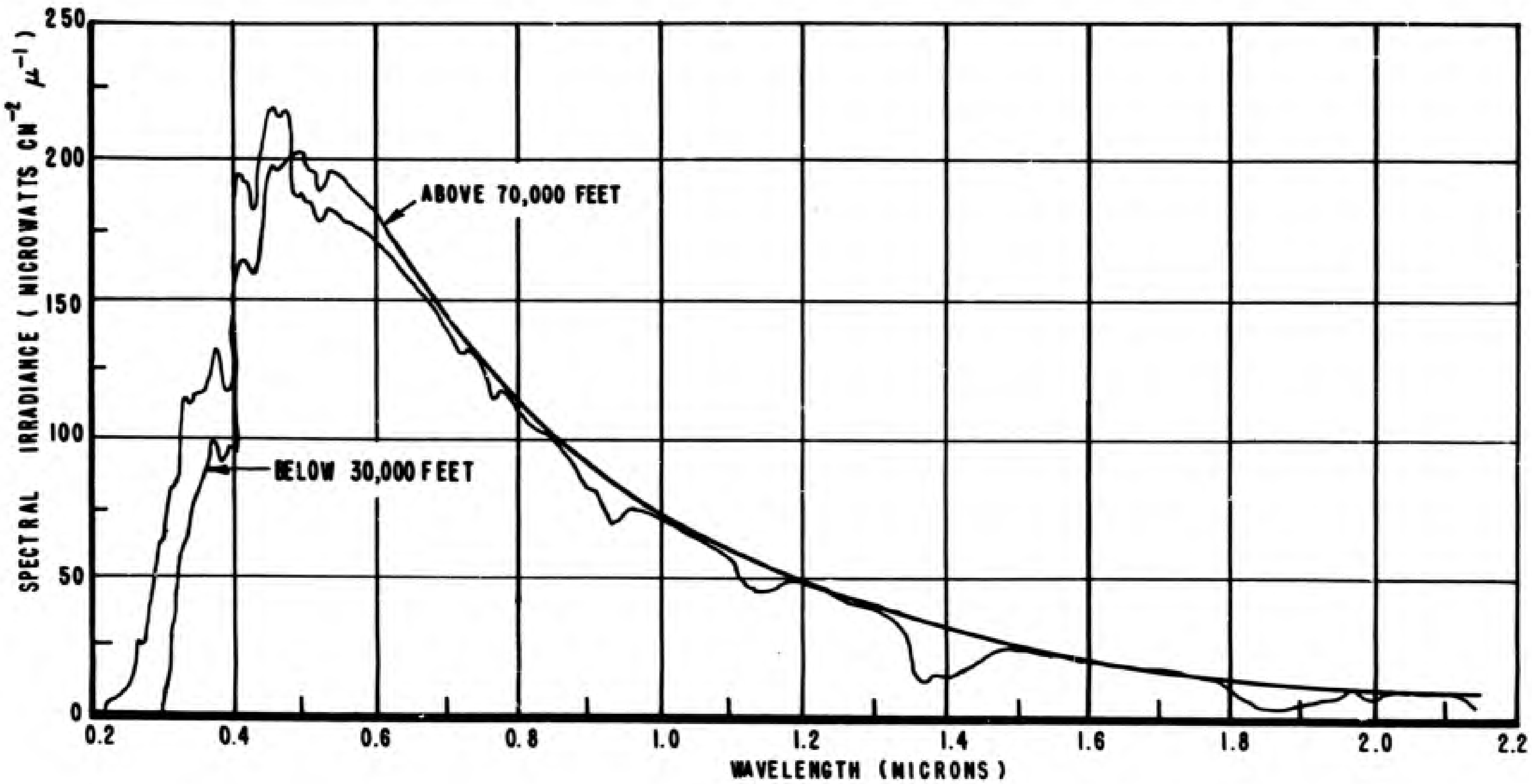

Figure 2. Solar Spectral Irradiance

an integrated point source and as such can protect a large volume by properly enclosing the volume.[1] Continuous types do not normally enclose the area for efficiency reasons; the continuous type is, therefore, the most useful for maximum coverage of the area to be protected and has the best probability of receiving enough convective heat to provide an alarm.

Other fire detectors will not be considered because continual screening has indicated the unsuitability of applying them to aircraft.

b. Overheat Detection

Overheat detection implies a rise in the ambient temperature but does not imply necessarily the presence of a fire. Detectors must, therefore, be able to cope with temperature-level discrimination and nothing else. With respect to the argument previously put forth for the use of the continuous sensor for fire detection, it can be readily seen that it applies equally well to overheat. Since this detector is not specific for fire or overheat, it will be considered in the summary. Radiative transfer devices could be used to detect a change in the temperature of the background, but their optical paths, field of view, and locations would require specific engineering for each vehicle. No aircraft use of "pyrometers" of this type has been made and as such they will be precluded from consideration until such time as their use becomes practicable.

c. Explosion Detection

Most operational aircraft require no explosion detection devices for engine nacelles. It is justifiable to exclude this concept, because the vehicles considered are such that explosions are extremely rare and are normally the secondary result of a fire. For future manned flight vehicles, however, this is not the case. Mach numbers as high as 8 and fuels such as hydrogen must be considered. Explosion detection would then be of benefit because complete automatic compensatory action could reduce hazardous overpressures to a safe level and allow the vehicle to remain intact. If the vehicle were to be subjected to ensuing explosions, it would be possible to augment information to automatic ejection systems to provide enough lead time for escape. Explosion detection for these purposes can be accomplished best by sensing either the infrared or the ultraviolet radiation rate of rise. It is also possible to locate the origin of the explosion and determine its potential destructive ability. With appropriate electronics, suppressants can be fired into the flame front and reduce reaction rates and overpressures to an acceptable level. Infrared detectors are presently being used in surge tanks of commercial aircraft for lightning protection; laboratory tests have verified their usefulness. Unfortunately, infrared detectors are subjected to saturation light levels or high ambient temperatures, thus reducing their effectiveness in an engine nacelle. Since ultraviolet detectors, however, do not have this drawback, they would be preferred for this use.

Pressure sensors for explosion detectors have many shortcomings. The basic ones are as follows: The time lag between radiation emission and detectable pressure rise is in the order of at least a few milliseconds optimistically speaking. Propagation time to the transducers is a function of distance and wave-front velocity and can add substantially to total detection time. Pressure rise need not indicate only an explosion; thus care in determining settings for different altitudes and different hazardous conditions would have to be taken. Although pressure transducers can provide fundamental detection for an explosive occurrence, it is not an adequate solution for manned flight vehicles for other than a stopgap solution. Pressure transducers of the differential type for altitude compensation are usually classed in the preset "go-no-go" category.

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[1] The continuous sensing elements provided for aircraft use today take advantage of many different techniques such as expansion of a trapped gas or thermionic conversion to electrical power. For this report all techniques are considered as equivalent.

d. Summary

For fire detection, per se, the infrared, ultraviolet, and continuous sensor will be considered as acceptable. From the point of view of specificity, however, the radiation sensitive devices are the only suitable devices. Continuous detectors can distinguish between different rates of rise of the ambient temperature and trip for fire on a maximum acceptable rate of rise and overheat on a minimum rate rise. The difference between the situations is quantitative, not qualitative, and thus the detector can perform primarily as an overheat detector and secondarily as a fire detector. The choice between an infrared and an ultraviolet fire detector cannot be resolved except from a systems basis; that is, only specific applications could possibly preclude the use of either one detector or the other. For example, an exceptionally high, normal, ambient temperature, and the accompanying increase in blackbody radiation, could conceivably swamp out an infrared detector, but not adversely affect the ultraviolet detector. The only other possible constraint for the infrared detector would be the time required to discriminate and automatically extinguish the flame. In 15 or 20 cycles, the overpressure or combustion rate could increase beyond the control of an actuated squib. Normally 40 or 50 milliseconds are adequate for total detection, discrimination, squib firing, and encountering the front with the suppressant, which allows only 5 or 10 milliseconds for effective detection and discrimination.

At 15 CPS a single cycle would take 66 milliseconds and not make any decisions on discrimination. The ultraviolet detector, not burdened with this problem, can detect within 100×10^{-6} seconds and discriminate in less than 1×10^{-3} seconds, allowing most of the total time to be spent on activating the appropriate compensatory devices. From the foregoing analysis, the ultraviolet detector is the best explosion-detection device although it works equally as well also as a fire detector. If the electronic filtering on the infrared filter is bypassed, explosion detection and discrimination become possible. Infrared detectors in this mode can be used for explosion detection while still maintaining their fire detection capability. The time allotment of 40 to 50 milliseconds is based upon hydrocarbon explosions in closed compartments, and fires are considered as having many seconds of time available for safe detection.

The preceding discussion resolves some of the decisions required later for the design of a computer by verifying the importance of the detectors used and for which tasks they are best suited.

3. MAXIMUM UTILIZATION OF SYSTEM CONCEPTS

To take advantage of integration of the three detectors, ultraviolet, infrared, and continuous, requires several decisions to be made. The first decision is that of maximum utilization. This could be best defined as adequately protecting the largest operational aircraft with the highest operational capability. Typically this results in the choice of an eight-engine, jet-powered aircraft. Each engine of this aircraft must be protected adequately requiring more than one of each of the three detectors. The location and choice of the number of detectors will be discussed later. If it is assumed that the same computer can be used for a multiengine aircraft as well as a single engine aircraft, a distinct advantage becomes apparent. A single stock-number device with a large amount of statistical data to support its reliability can now become available. Redundancy, built in for the multiengine aircraft, now becomes multiple redundancy for the single engine aircraft. All that is required is that special programming for the same computer be accommodated. The difference in installations will be resolved more specifically later in this report.

All three detectors will be used in all installations regardless of the fact that an explosion would not occur. The exclusion of explosion detection is a programming problem and not a computer design limitation.

To simplify system design a single engine configuration will be used. The installation for a single engine is shown in Figure 3. This shows diagramatically the location and number of transducers required. An explanation of the reason for this choice is given in the following discussion for each type of detector:

a. Overheat Detection

The detection of overheat is a problem that is specific with the type of aircraft to be protected. The direction of air flow and the flow rate are two of many influencing factors. For the maximum possible reliability, the location will be theoretically determined rather than empirically. This allows the optimum number of detectors to be selected and a reasonable predictable result to be made. Two parallel cables (continuous sensors) side by side will be

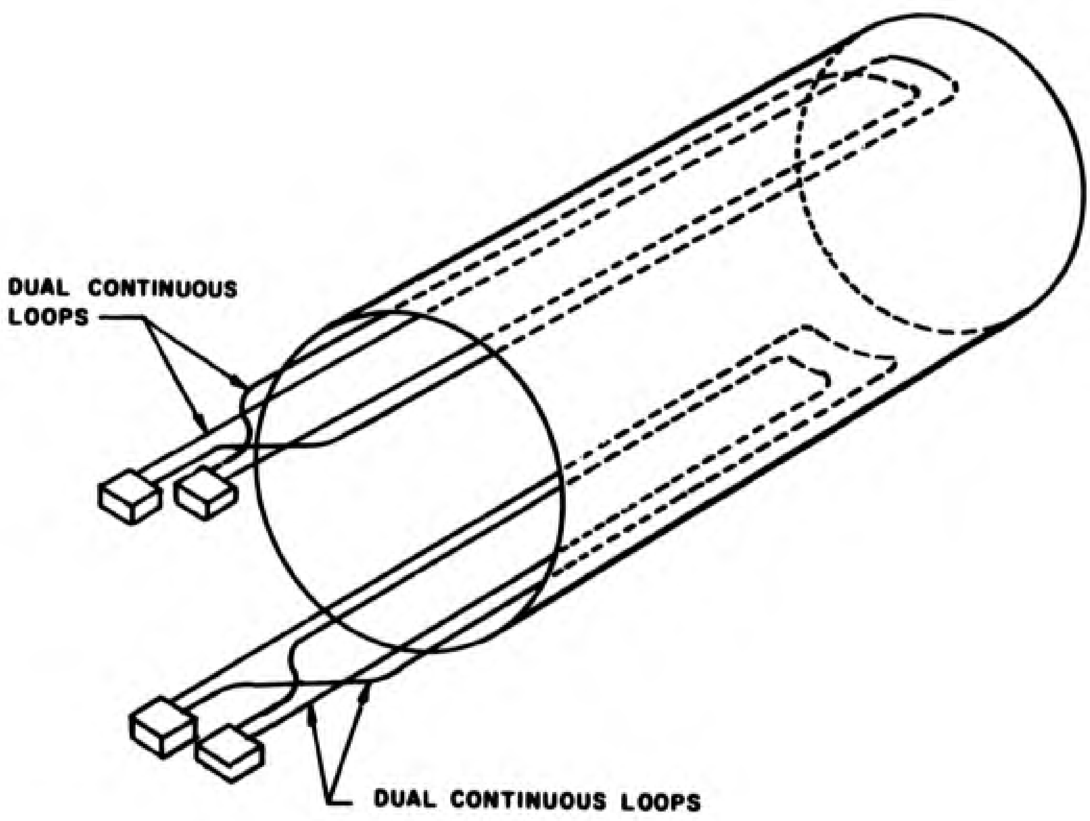


Figure 3. Installation of Overheat Detectors in a Single Engine Nacelle

used for each area to be protected. One cable will detect overheat and the other will verify it. As shown in Figure 3, one pair of cables is installed at the top of the engine nacelle and other at the bottom of the engine nacelle. Since this is only an overheat detector, an abnormal ambient temperature rise could be expected to trigger at least one pair of detectors. Self verification of the cable pair allows for the simplest form of redundancy. See Table I.

b. Fire and Explosion Detection

Both fire detection and explosion detection will be considered as a single concept from the concept of locating the detectors. Since infrared and ultraviolet detection would both be useful for explosion detection and since they both are good fire detectors, this decision is logical. The placement of multiple detectors requires not only an engineering decision as to the location of the devices but also the exact number of devices. A logical decision must be made at this early stage which will have a large influence on the design of the computer. Considering only ultraviolet and infrared, fire detection can be provided by two methods (Table I)

1 { Infrared (Primary)
  Ultraviolet (Verification)

2 { Ultraviolet (Primary)
  Infrared (Verification)

Fire detection must always rely on at least two types of detectors, and primary detection will be accomplished by the fastest method, radiation detection. If primary detection is truly supposed to be the fastest method, then complete volume coverage by the sensors must be accomplished. Figure 4a through 4c illustrates several methods for doing this.

If ultraviolet and infrared sensors are used in alternate locations, multiple problems soon become evident. For Figure 4a Sensors 1 and 3 could be ultraviolet and Sensors 2 and 4 could be infrared. Overlaps in the "cones" of the field of view of the detectors provide the only possible volumes of direct verification. If Sensor 2 (infrared) fails, the zone between 1 and 2 no longer has direct verification. Indirect verification by reflection to some other sensor is possible, but it cannot be depended upon for maximum reliability. With this concept, a single sensor failure would constitute a system failure due to the lack of direct verification. Figure 4b has more areas of mutual overlap in the sensor detection "cones" and provides an interesting contrast to Figure 4a. If, in Figure 4b, Sensors 1 and 2 are infrared and Sensors 3 and 4 are ultraviolet, a single system failure results in only a partial loss of direct verification. If a cone angle of 90° is used to maximize optical gain for the sensor, while providing the largest field of view, then the following analysis can be made. An engine nacelle, typically 4 feet in diameter by 20 feet long, illustrated in Figure 5, will be used for this analysis. The unusual shape of the "cone" illustrates that the overlap will normally be less than 50% between two adjacent cones. The failure of one sensor truly does leave some minimal area completely unprotected, but this would vary in different types of aircraft.

Figure 4c illustrates the case where any single sensor failure will not affect the system. Eight sensors widely dispersed in this manner require multiple connecting cables and housings to provide this capability, however; as such it is far from a practical solution to the problem. The apparent requirement for eight detectors can be reconciled by using the arrangement in Figure 4b, and integrating two detectors, ultraviolet and infrared, into a single sensor head. Now a single detector failure does not constitute a single detector head failure, and all zones will have 100% verification. When the detector head concept is used for two sensors, many possible configurations now become possible. An example of an installation is shown in Figure 8. This installation uses three sensor heads and six detectors and would adequately cover a typical 4-foot by 20-foot nacelle. Figure 4c and Figure 7 typify the basic optimum installations to provide 100% fire verification even with a single detector failure.

TABLE I

DETECTOR SELECTION AND USE

For Overheat Detection

1	Continuous (Primary) Continuous (Verification)

For Fire Detection

1	Infrared (Primary) Ultraviolet (Verification)
2	Ultraviolet (Primary) Infrared (Verification)
3	Infrared (Primary) Continuous (Verification)
4	Ultraviolet (Primary) Continuous (Verification)

For Explosion Detection

1	Ultraviolet (Primary) Ultraviolet (Verification)
2	Nonelectronically Filtered Infrared (Primary) Nonelectronically Filtered Infrared (Verification)
3	Ultraviolet (Primary) Nonelectronically Filtered Infrared (Verification)
4	Nonelectronically Filtered Infrared (Primary) Ultraviolet (Verification)

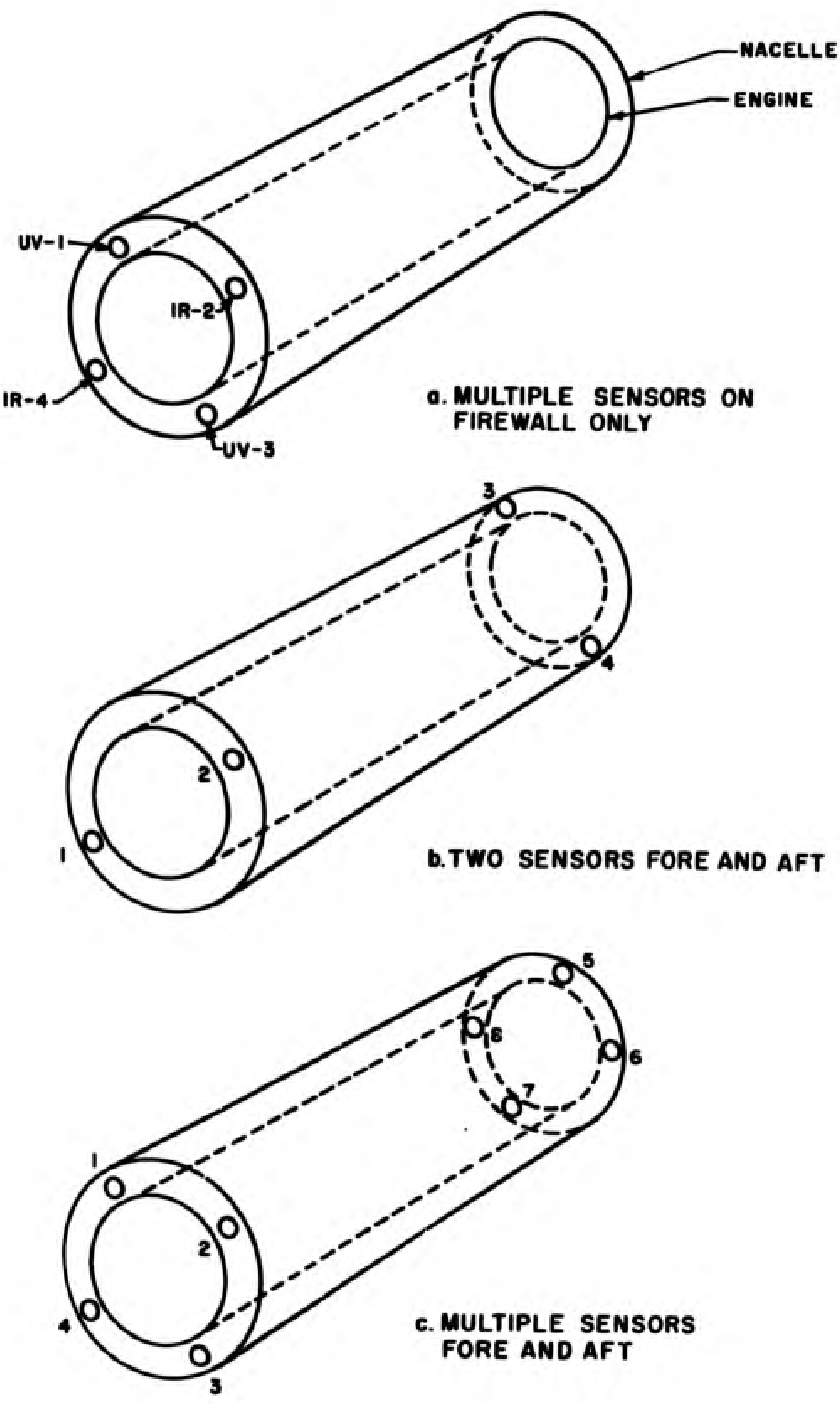


Figure 4. Methods of Locating Multiple Sensors

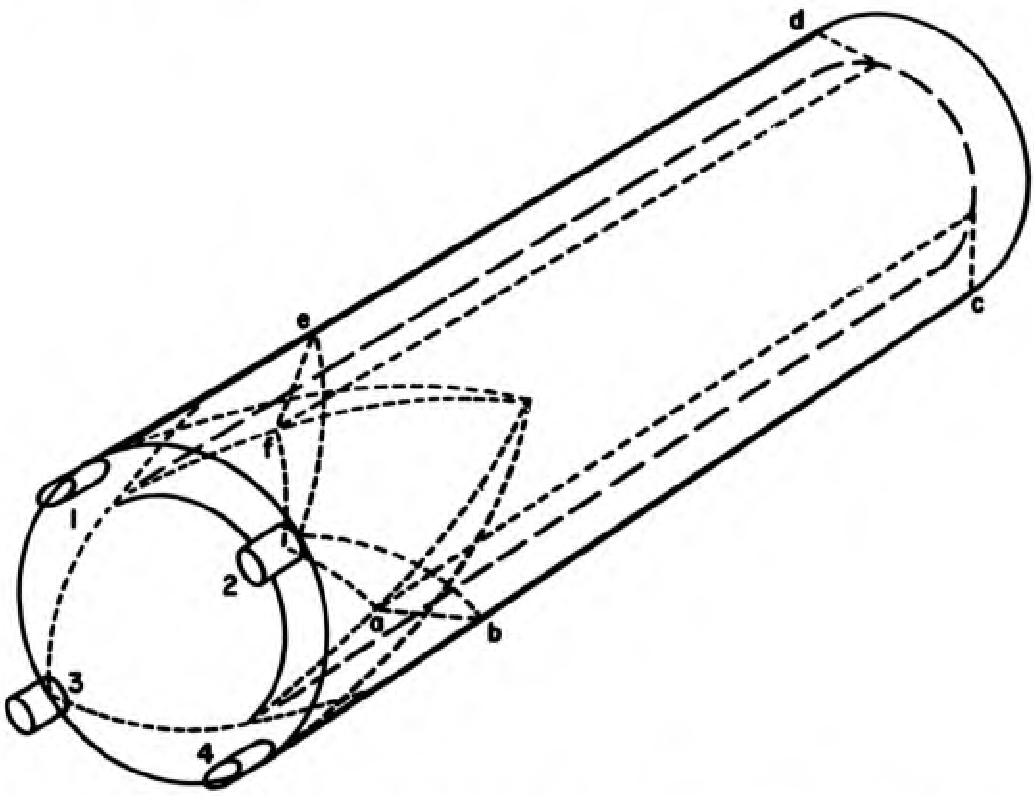


Figure 5. **Multizone Coverage in Engine Nacelle by Ultraviolet and Infrared Sensors**

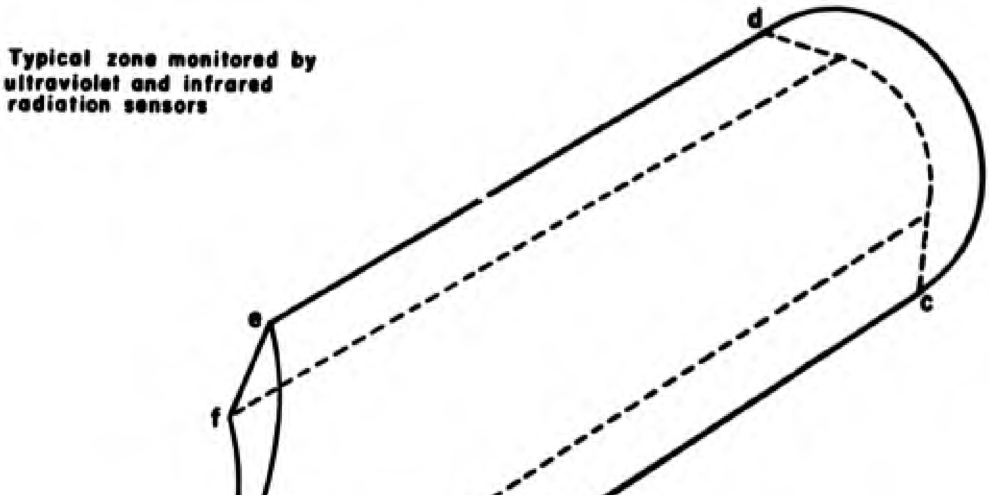


Figure 6. **Single Zone Monitored in Engine Nacelle by Ultraviolet and Infrared Sensors**

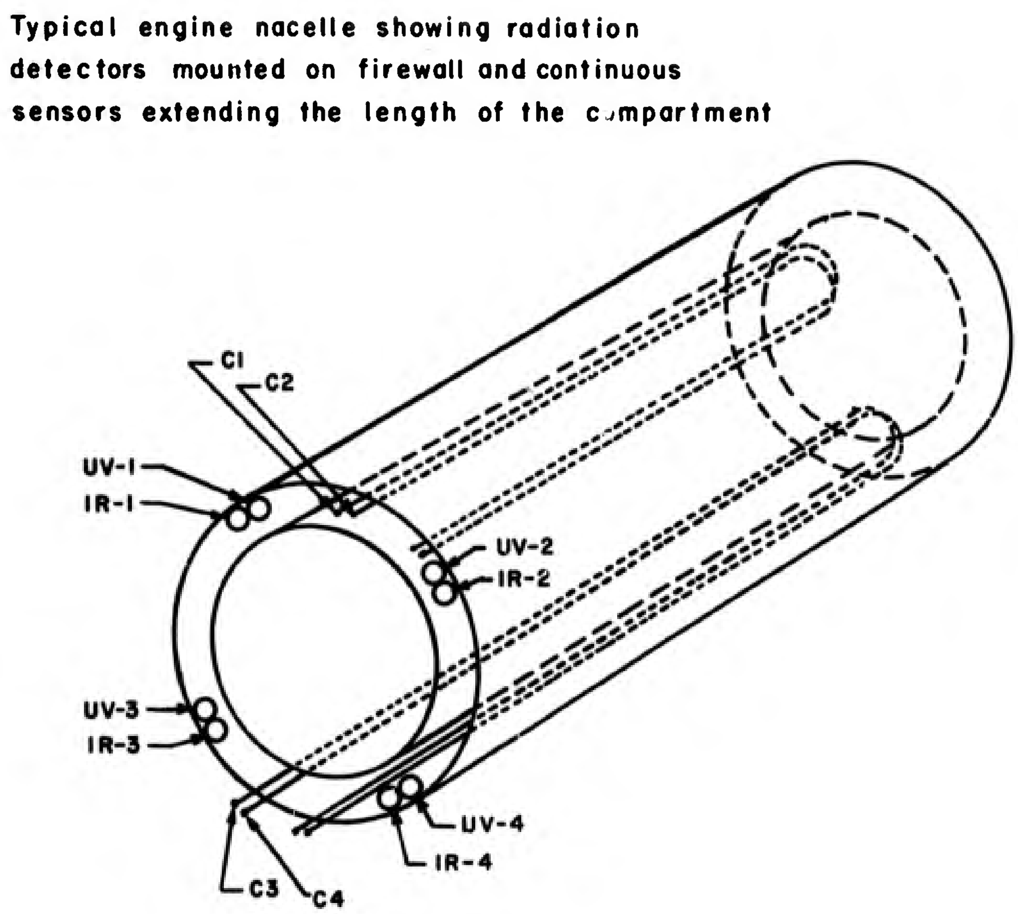


Figure 7. Sensor Locations in Engine Nacelles

Explosion detection should be more judiciously labeled explosion discrimination. The only difference between a fire and explosion is the rate of propagation of the combustion front. An explosion can be deflagrative or detonative depending upon whether the wave front travels subsonic or supersonic, respectively. A fire detector used for explosion detection must, therefore, discriminate between rates of rise of the incident radiation, and, after a small but finite time period has elapsed, make the decision as to whether this rate of rise will top off at some level or whether the rate of rise truly indicates an explosion and continues to rise.

When discrimination for a known geometry is attempted, the problems can be lessened somewhat. Figure 8 typifies a technique for three-dimensional monitoring using two detectors facing each other surveying the same volume. The figure illustrates the ideal problem and, as discussed later, cannot realistically typify any particular installation. Detectors, or sensor heads with infrared and ultraviolet detectors, are paired up to survey the same volume. Thus, Sensors 1 and 4, 2 and 5, and 3 and 6 comprise single units of the explosion system. When detectors are paired, the precise location of the flame can be determined. For example, using Sensors 1 and 4 as a system the following analysis can be made: If a fixed flame occurs exactly between Points 1 and 4, the radiation levels to the sensors will be equal. When their analog response is compared, as shown diagrammatically in Figure 9, it is possible to locate the flame because the differential output will be zero. Now let the flame occur directly in front of Detector 1. The change of output of Detector 4 will be a maximum while the distance squared loss of the radiation to Detector 1 will cause only a very slight change in it.

If a known level of radiation is to be expected, then this system could be calibrated in feet. Radiation levels will be different from that of a finally stabilized flame, so that nonlinear correction factors for flame size and detector nonlinearities would have to be compensated for. For the judgment as to the size of the flame, a single detector could be calibrated as a pyrometer and a meter or numeric readout giving a quantitative index could display it to the crew member.

Explosion discrimination by analog comparison of rates of rise from Sensors 1 and 4 would be effective only during the worst case when the rate of increase of radiation to both detectors approaches a maximum due to both an increase in the burning front area and the combustion front moving toward the sensor. This propagation of the flame front is the basic tool for defining the difference between a "harmless" flame and a moving flame front with accompanyingly high overpressures (in excess of 5 PSIA). When the maximum possible propagation rate is determined for stoichiometric mixture ignited in the middle of the chamber, a finite minimum time for detection and discrimination can be realized. Thus, if 50×10^{-3} seconds is required for total propagation, a factor of 10 less will amount to 5×10^{-3} seconds for maximum discrimination so that most of the total time is available for squib firing and suppression of the flame front. Rather than discuss the limitations and assets of an explosion detection system in detail, we will accept as a fact its usefulness as a function of installation geometry can be achieved. As proof of the concept, some present commercial airliners are currently installing explosion detection for their wing-tip surge tanks.

c. Summary

The application of the ultraviolet and infrared detectors to a single engine configuration depends upon the specific system to be protected. For maximum utilization of a single computer to handle a single nacelle, the maximum information to be handled must be determined. The individual computer need not cope with both fire and explosion for all cases. A low and slow multiengine aircraft is not as likely to have an explosion in the engine nacelle as would a supersonic aircraft. As far as can be statistically determined, operational supersonic aircraft presently have not been plagued by this type of hazard either. Future supersonic and hypersonic aircraft using higher combustion temperatures and exotic fuels are immediately laid prone to conditions that are optimum for a hazard of this type. It is with the forethought of its future use that explosion detection and discrimination will be discussed. So for present operational manned flight vehicles in the supersonic region, we are allowed to determine an approximate maximum use for the number of detectors required. Geometries will vary, but the number of inputs will not exceed worst case conditions.

The worst case still remains that of eight detectors: four ultraviolet and four infrared. When an ultraviolet and an infrared device are paired in a single sensor head, the requirements to the computer can be reduced somewhat.

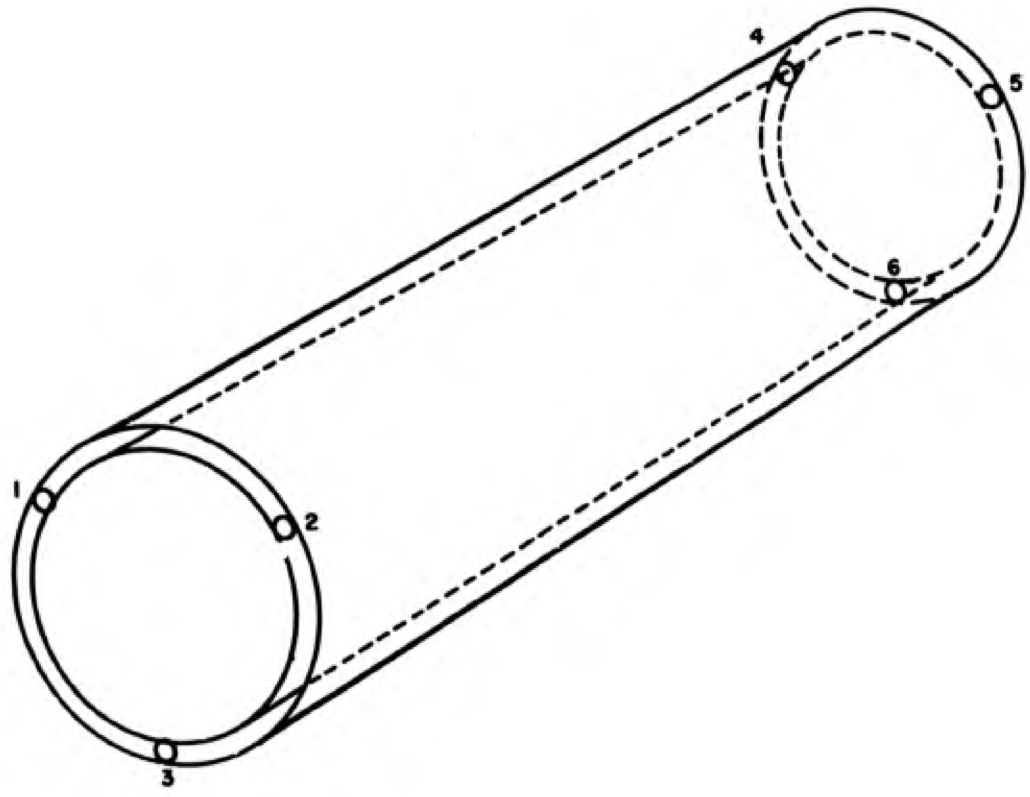


Figure 8. Explosion Discrimination Installation

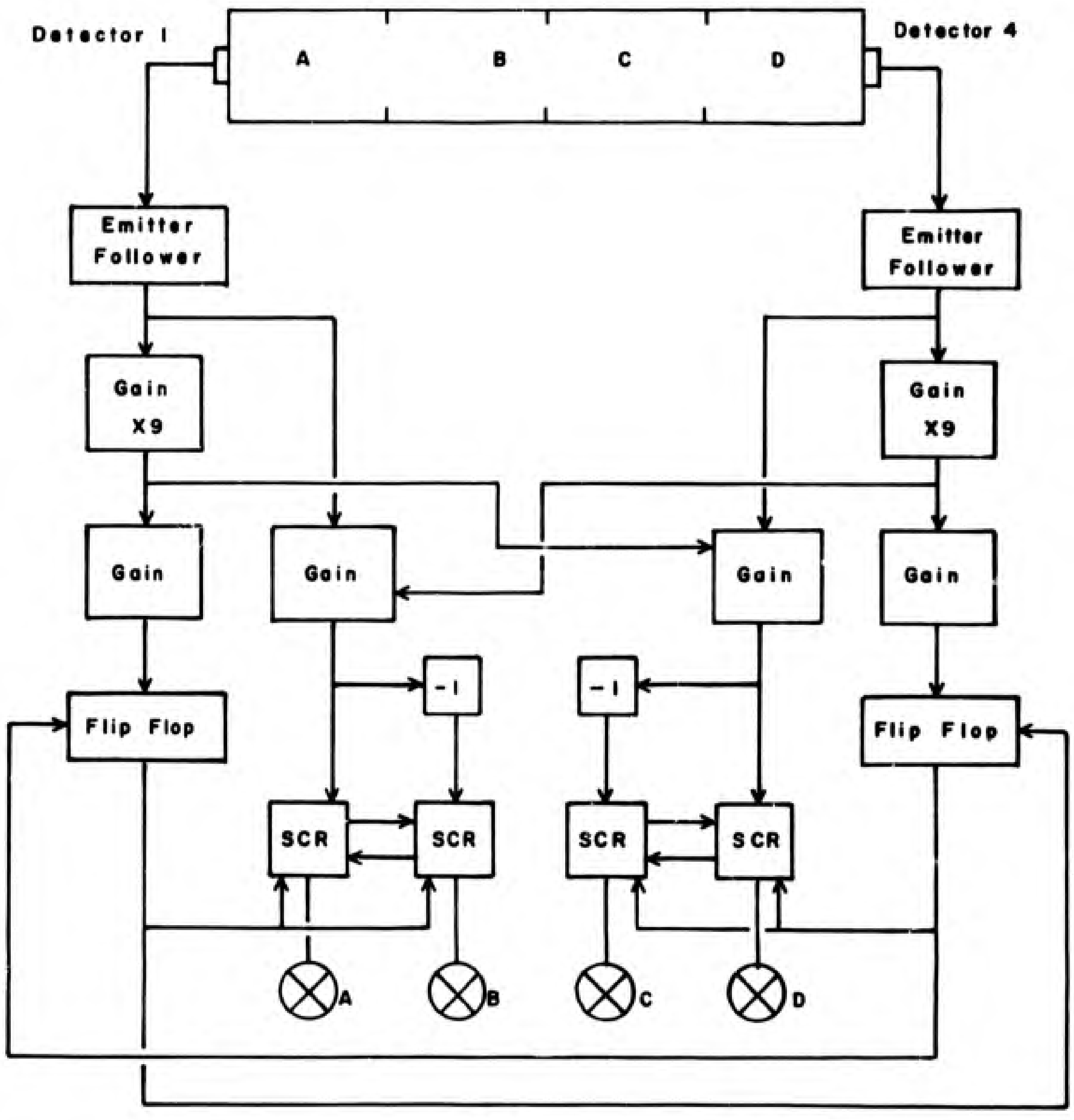


Figure 9. Block Diagram of Experimental Explosion Detection System

SECTION III

DESIGN CONSIDERATIONS

1. DETECTOR PARAMETERS

The circuitry to be used with the detectors is one of the basic keys to the maximum reliability. In this discussion, a step-by-step analysis of detector parameters will be made so that the maximum use of the detectors can be made.

a. Infrared

The basic consideration for the selection of an infrared detector must be made by analyzing the following characteristics:

(1) Spectral response

(2) Sensitivity

(3) Optical response times

(4) Aging characteristics (spectral shift, loss of sensitivity, etc.)

(5) Voltage and current requirements

(6) Temperature dependence

(7) Active or passive (photovoltaic, photoconductive)

An analysis of spectral response must be made at the temperature at which the detector will operate. Not only will the spectral response be shifted but signal-to-noise ratios at ambient temperatures near 250°C must also be considered. Lead sulfide, lead selenide, and silicon are typical of good photodetectors, but they cannot be used at or near the required 250°C ambients required. Silicon has been used with varying degrees of success due to the temperature limitations. Since detection must occur at radiation peaks well defined by flame emission spectra and in the least conflict with blackbody radiation, spectral shift must not be such that signal-to-noise ratios or sensitivity is substantially reduced.

Sensitivity can be clearly defined by characterizing the hottest part of the engine in a nacelle as a typical blackbody and applying approximations of Planck's radiation laws to determine the "noise." The signal required instantaneously to overcome this noise should be at least the same order of magnitude in intensity and considerably different in spectral emission. A flame from JP-4 fuel could by volume mask a blackbody radiator immediately behind it. Thus, modulation detection would be more pronounced than if the radiator (the flame) did not absorb and reradiate characteristically due to vibrational and rotational bands in the combustion zone. It is apparent that the absorption by a flame of the background blackbody radiation could affect the signal-to-noise ratio, especially if the acceptance cone angle of the detector is limited reasonably close to where the fire will encompass the maximum of the available field of view.

The optical response time for the infrared detector is a function of the semiconductor material used and its geometry. The ambient temperature can also affect mobility times in photovoltaic devices, but this effect is normally insignificant in the application of detectors for this use. Optical response of a fire detector is defined as the amount of time it takes a detector to change its electrical properties with modulated radiation falling on its surface. Quantitatively this analysis should be made with a spectral source that will cover simultaneously all the wavelengths the detector will respond to. A special analysis of the spectral emission of interest should also be made to verify response. This test would involve the use of a high intensity flame and an optical chopper. Results, however, are not normally too different in the two examinations except for thermal transfer to the detector itself which changes the nominal detector temperature. Response times of the order 5 milliseconds are typical.

Aging characteristics of detectors are important. Spectral shift as a function of aging must be controlled. Contamination or degradation of the detector material due to heat or vibration can occur unless a device has been qualified. Storage in dark areas for long periods of time can also contribute to unacceptable units until they are re-aged in light for a period of days. This type of short-term aging is important to realize especially when operational infrared detectors are replaced with ones stored in hermetically or dark sealed packaging. Detectors not properly light-aged will not qualify under initial electronic specifications, and complementary electronics designed to operate based upon the original parameters will not work properly.

Voltage and current requirements are generally characterized by the type of detector. Silicon devices are nominally low-voltage devices with moderate current capabilities and as such require little power or special filtering techniques to reduce sensitizing voltage ripple. Silicon does have "punch through" problems, however, and, if peak or "spike" overvoltages occur, a hole can be made in a PN junction of a photodiode to render it useless. All devices used as infrared radiation detectors are nominally low power devices and draw less than 1 watt. Some devices require electronic gain and filtering due to this characteristic, however, this is not considered a drawback where gain and filtering can be provided elsewhere other than in the high ambient of the engine nacelle. A typical sensitivity versus wavelength of an infrared cell which can be used for fire detection in aircraft is shown in Figure 10.

The temperature dependence of the detector for its use as a fire detector is a true indication of its overall usefulness. As the temperature approaches the maximum ambient conditions expected, spectral shift, loss of sensitivity, and change in electrical properties cannot be tolerated. Thus, the detector must be able to operate continually at the expected level of the ambient temperature. Cyclic ability from lower temperatures to higher temperatures must not affect operation either, for arctic operation or desert operation extremes could be a common day-to-day environment. Present-day devices can be designed to fulfill these basic requirements although there is a compromise made in performance over this range. Any similarity between the use of infrared detectors for fire detection and those used for other purposes is strictly not candid.

Active versus passive detector cells. This statement expresses the problems of electronics design, "quantum efficiency," environmental suitability, plus all the problems normally attributed to designing for use with a specific vehicle. The choice of the mode using a detector that can be either a photoconductive or a photovoltaic device requires insight into the specifics of the problem. Thus the decision to choose either a photoconductive or photovoltaic device is really a function of the device dynamics. A typical silicon-type photovoltaic infrared cell can generate adequate power to drive simple transistor circuitry that is remote from detector. An output voltage of 300 millivolts is typical, and rise times of the pulse is in the order of microseconds when instantaneously saturated by radiation. A photovoltaic output pulse showing the response to an optical chopper wheel illustrates moderately good compliance to a step function type of optical input. In this instance this type of detector could be used for explosion discrimination on hydrocarbon fuels with an adequate margin of safety for compensatory action such as squib firing.

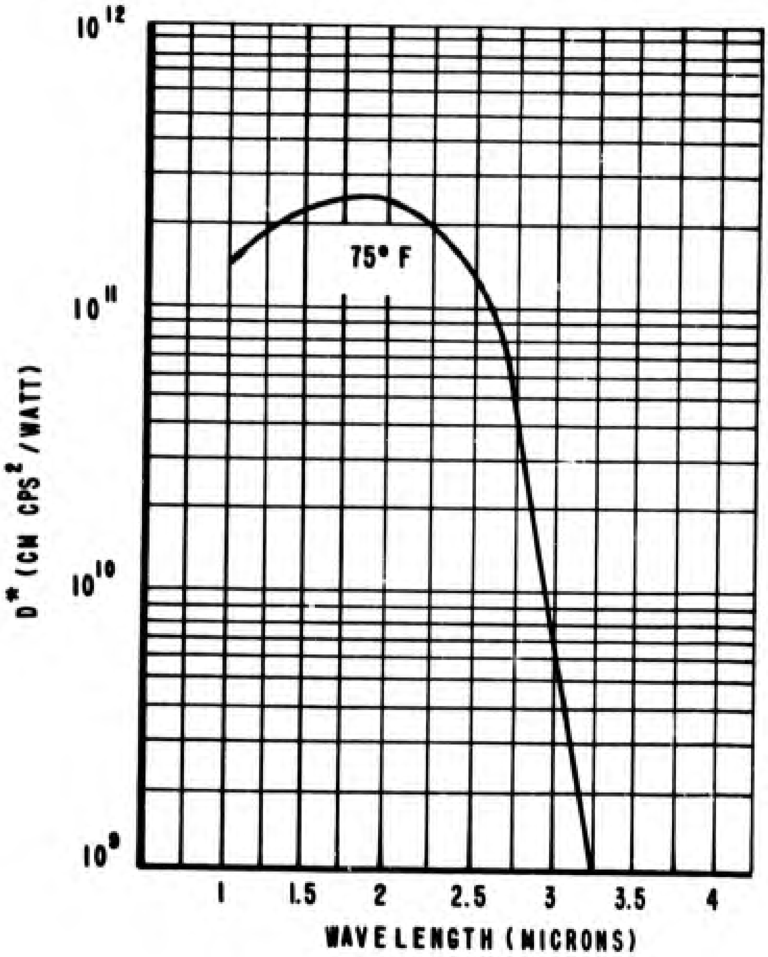


Figure 10. Infrared Detector Sensitivity Versus Wavelength

b. Ultraviolet

The analysis of ultraviolet detectors considers two different types of detector. The first type, a solid state device which is either a photoconductive or photovoltaic device, is basically covered under the previous infrared analysis. Additional commonalities as well as acute differences in these devices will be discussed further. The second type of device is the solid metal cathode, gas-discharge, Gieger-Mueller-type tube. This detector will be analyzed on a simple basis and its assets and liabilities outlined.

(1) Solid State Devices

A discussion of ultraviolet, solid state devices will follow the pattern setup for the infrared detector analysis. This discussion will deal only with silicon carbide (SiC) detectors.

Spectral response of a SiC detector can be tailored somewhat for this particular problem. Unfortunately spectral tailoring cannot produce a solar blind device, that is one operable with response only below 285 nanometers. Peak sensitivities at less than 285 nanometers at 25°C are possible, but "tailing" prevents the longer wavelengths from being excluded from detection. As the temperature increases, the peak sensitivity of the device shifts to the longer wavelengths and cannot be used as a solar blind detector even with filtering. The spectral response of the device still lies within the primary ultraviolet radiation bands from a hydrocarbon or hydrogen fuel combustion process and as such can be used for fire detection. Where insensitivity to solar radiation is of no problem, the device can be applied. Spectral peaks at 300 nanometers at 1000°F are present capabilities of these devices (Figure 11). Silicon detectors presently have shown nominally low sensitivity to ultraviolet radiation from flames even though there is extended short wavelength response down to 200 nanometers. These devices have little potential use for this type of application primarily because of this problem and temperature limitations and will not be considered further.

The present quantum efficiency of SiC devices is above 0.1%. These devices, photovoltaic types, require judicious handling in order to be used as flame detectors. Minority carrier times of the detectors are such that high-frequency optical response would normally be expected. Optical modulation rates for testing the detectors indicate single cycle times of about 5 milliseconds which can be improved.

The problem of aging does not seem to be manifest. Leaving devices exposed to radiation or in a light-tight enclosure does not appear to affect sensitivity nor spectral response. The voltage and current characteristics of devices require buffer or signal conditioning circuitry to maximize the signal strength and reduce noise levels. Reverse biased photodiode operation appears best for this type of application. This mode of operation can be improved eventually by using newly developed SiC transistors and diodes as required.

Active device designs using photovoltaic outputs are currently being developed, although it is felt that the back-biased photodiode will eventually prove more effective. Devices of this type should last the life of a flight vehicle provided all considerations for detection can be tailored into the device.

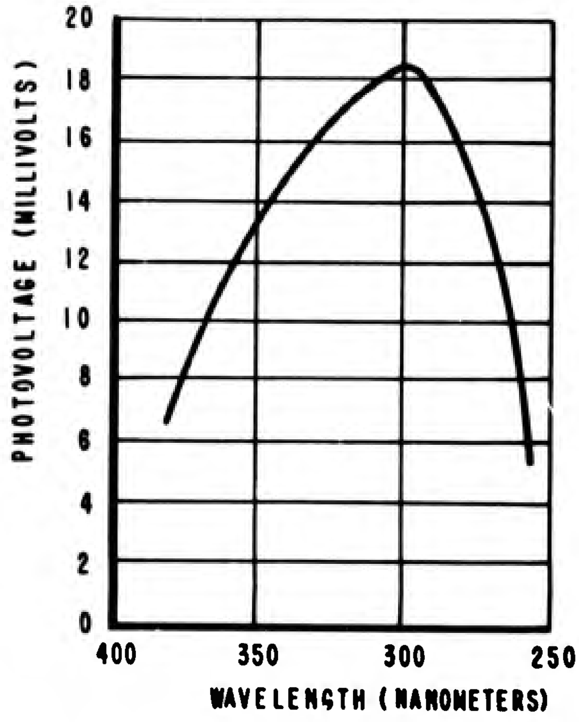


Figure 11. Ultraviolet Silicon Carbide Detector Photovoltage Versus Wavelength

(2) Gas Discharge Tubes

These detectors are ultraviolet transmitting, glass envelope, gas-filled, metal photocathode devices commonly referred to as Geiger Mueller tubes. Ultraviolet radiation penetrating the envelope strikes the metal photocathode releasing a photoelectron. The electron ionizes the gas and an electrical pulse is formed. The deionization of the gas completes the pulse.

The spectral response of the detector is basically between 200 and 280 nanometers using a tungsten photocathode. Peak sensitivities between 210 and 230 nanometers are typical (Figure 12). When stringent controls are used during the processing of these tubes, near perfect solar blindness can be achieved at altitudes up to 32,000 feet without special electronics or optics considerations. No noticeable spectral shift during operation occurs in a good tube. Poorly processed tubes do, however, have this drawback. Apparent quantum efficiencies of 5×10^{-4} are to be expected, although improvements in both window material, geometry, and cathode processing can possibly improve this by more than 1 or 2 orders of magnitude.

Laboratory tests reveal optical frequency response times approaching 1×10^{6} Hertz. This feature does not have any particular significance because the total number of pulses can be varied by the damping circuitry. Previous uses of this tube indicate that a high count rate is undesirable due to lack of stability and difficulty in obtaining an adequate signal-to-noise ratio.

One of the major problems of using a detector of this type has been that of providing the sensitizing voltage required to trigger the tube. At least 350 volts RMS has been required for past detection systems (nonaircraft) using this tube with 750 volts peak being a more typical

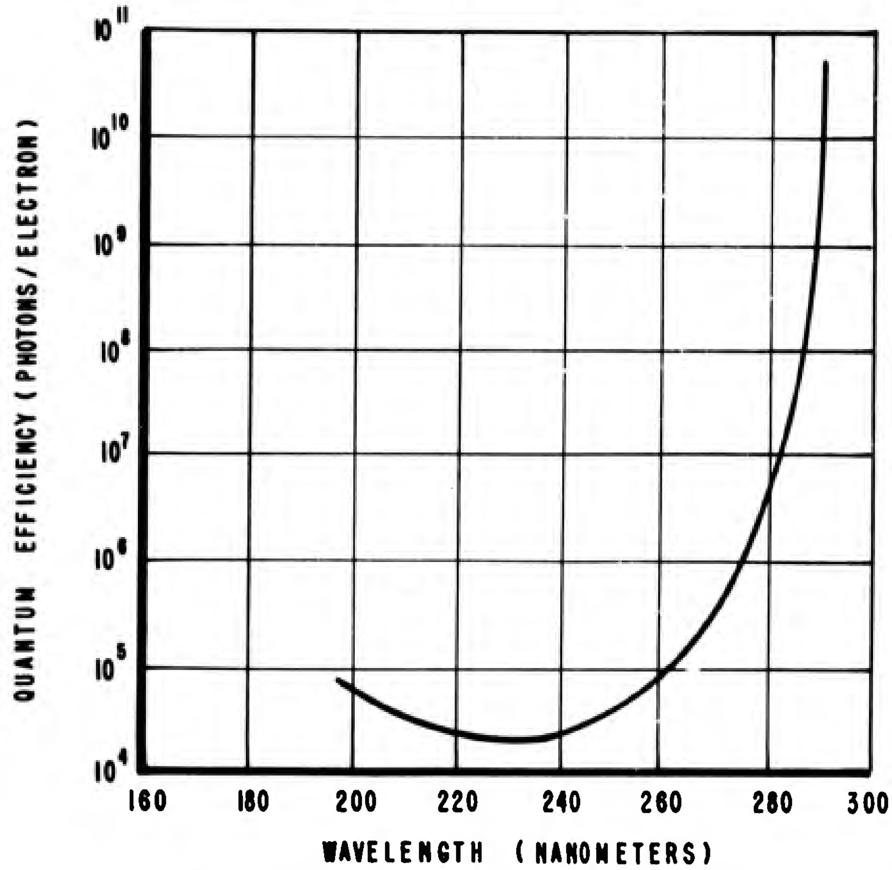


Figure 12. Ultraviolet Tube Detector Sensitivity Versus Wavelength

value. Tubes presently under development are designed to operate at 200 volts which substantially reduces the problem of design for high altitudes.

(3) Other Types of Ultraviolet Detectors

Many other types of ultraviolet detectors are available for aircraft fire detection. Cadmium sulfide and cadmium selenide ultraviolet detectors are available as photoconductive devices, but their temperature limitations and poor response times immediately preclude their use (Figure 13).

Multiplier phototubes have been built to operate at 1000°F. Their high voltage requirement, photocathode limitations, and susceptibility to damage from high frequency vibration make these devices an unwise choice. Voltages over 1000 volts DC are necessary for maximum gain which results in a connector problem at high altitudes.

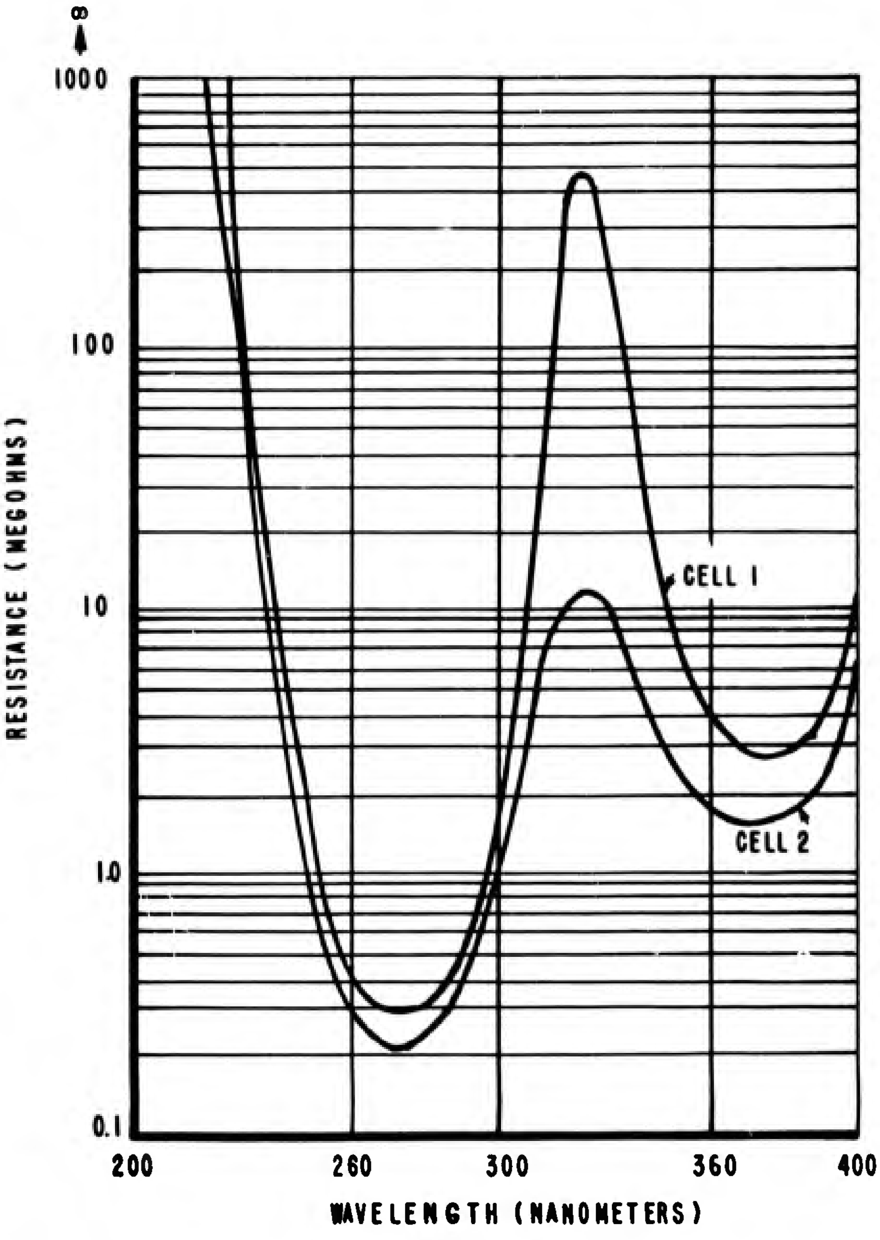


Figure 13. Cadmium Sulfide Ultraviolet Detector Sensitivity Versus Wavelength

2. DETECTOR ELECTRONICS

The technique used for fail-safing the detectors individually is shown conceptually only, and refinements in design are not given. Each ultraviolet, infrared, and continuous detector type is treated individually to illustrate the necessary fundamentals for design and to point out basic limitations.

a. Infrared

The use of an infrared cell such as lead sulphide (PbS) has many drawbacks. Previously outlined problem areas will not be discussed in detail here. Basically this analysis will be confined to applications problems, thus all parameters will be lumped together to present a more wieldy problem.

The basic problem is to detect a flame whose blackbody equivalent is 1800°F while in a 1000°F ambient. A PbS detector is far too sensitive to be left exposed to a flame or hot background directly, so it is desensitized by a spectral filter-attenuator to sense a 4-inch pan fire of a hydrocarbon fuel only 6 feet away at room temperature. Since this is only sensing and not discrimination, a 20-CPS or low frequency, low pass filter is used for discrimination.

The filter must be bypassed and the fail-safe discriminator circuit inserted directly to the detector. The output of the detector should not be modified so that its input to the filter remains unchanged. When a fire is detected, both the filter output and the fail-safe electronics must be required for an output. This can be accomplished by using an AND gate. The output from this gate is 5 volts. When the sensor does not see a fire and it has not failed, the output of the detector head will be 10 volts. Should a failure occur the output would be zero volts. In summary 10 volts means ok, 5 volts means fire, and 0 volt means fail. The output is a single wire for the signal and the power supply ground for the ground wire thus allowing only three wires to be run to each detector head.

b. Continuous

The continuous overheat detector is essentially an iterative thermocouple and as such will be treated as one. If the element "sees" no overheat, then a 10-volt DC output must be transmitted out of the detector "Black Box" to indicate ok. This can be done by either continuously or continually checking for continuity or capacitance, or other specific parameters. If an overheat is sensed, an output voltage triggers a threshold device to supplant the 10-volt output with a 5-volt output. If the sensor fails, a failure precedence circuit takes action negating any other output and causes 0 volt to be the output. Thus the performance is similar to the infrared sensor, and, as such 10 volts means ok, 5 volts mean overheat, and 0 volt means fail.

c. Ultraviolet

A solid state photovoltaic or photoconductive ultraviolet cell is basically the same as an infrared cell except for two differences. The obvious difference is that of wavelength sensitivity. The second difference, discrimination by wavelength as opposed to flicker frequency, allows ultraviolet sensors to activate the computer almost directly. Previous decisions to use 10 volts, 5 volts, and 0 volt for ok, fire, and fail are also, therefore, valid.

d. Summary of Total Outputs

Since each of the 12 individual sensors will have three outputs, there is a total of 36 inputs to the computer in trinary coding. All three systems use the same design philosophy so that the readouts OK, FIRE, OVERHEAT, and FAIL are the result in the same output voltages. The output voltages were chosen, both to be of a high enough level to avoid signal-to-noise ratio problems, and also to be compatible with existing microcircuit chips available "off the shelf."

SECTION IV

COMPUTER DESIGN

Now that most of the inputs and outputs of the computer have been defined, the actual design of the computer will be discussed.

1. DECODING OF TRINARY INPUTS

To decode the inputs to the computer from each sensor requires the following technique to be used: With 0, 5, and 10 volts input, two separate outputs of 0's and 1's must be provided so that binary coding can be used throughout the computer. To accomplish this, Figure 14 illustrates the computer building blocks used.

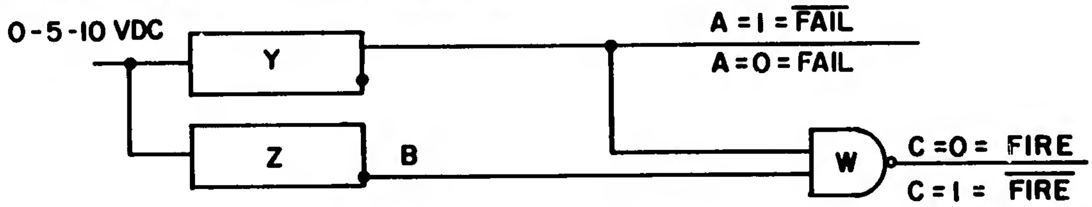


Figure 14. Trinary Converter

Block Y is a monostable multivibrator with a nominal onset voltage of 5 volts, and Block Z is a monostable multivibrator with a nominal 10-volt onset voltage. The final block, W, is a simple NAND gate. With 10 volts input, both Y and Z are turned on. W is not turned on because a 1 is input from Y but an inverted 1 (or zero) is input from Z which will not activate W. Thus W has an output of 1 which is $\overline{\text{FIRE}}$ (not fire - any word with a bar above it indicates inverting its meaning). Output A is a 1, which is $\overline{\text{FAIL}}$. (Not fail is used for OK.) The system is, therefore, OK and there is no fire present.

When a 5-volt signal reaches the input, only Y will be turned on. Output A will be $\overline{\text{FAIL}}$ and Output B into W will be a 1. With two 1 inputs to W, one each, respectively, from A and B, the C output will be a 0. A "0" at the C output means FIRE, and when used with a 1 from the A output, the system is operating OK or $\overline{\text{FAIL}}$. The final case is for 0 volt in. For this case the A output is 0 and the B output is 1. A 0 and a 1 input into W results in a 1. This states that A indicates FAIL and C indicates $\overline{\text{FIRE}}$. The conversion of trinary (0, 5, and 10 volts) to binary (0's or 1's) is shown in Table II.

TABLE II

TRINARY DECODER FOR COMPUTER INPUT SIGNALS

Input Volts	Failure A	Output B	Fire Mode C	Literal Meaning
10	1 (NOT FAIL)	1	1 (NOT FIRE)	NOT FIRE, NOT FAIL
5	1 (NOT FAIL)	0	0 (FIRE)	FIRE, NOT FAIL
0	0 (FAIL)	0	1 (NOT FIRE)	NOT FIRE, FAIL

For a total of 12 trinary inputs to the computer, there are now 24 binary equivalents. For clarity symbols will be assigned that will not become cumbersome during the Boolean expression formulation phase. Table III gives these assignments.

TABLE III

BOOLEAN SYMBOL ASSIGNMENTS FOR TRINARY DECODER

Zone Covered	Sensor	Fail Channel	Fire Channel
1	UV1	A_1	C_1
1	IR1	A_2	C_2
2	UV2	A_3	C_3
2	IR2	A_4	C_4
3	UV3	A_5	C_5
3	IR3	A_6	C_6
4	UV4	A_7	C_7
4	IR4	A_8	C_8
1,2	Con1	A_9	C_9
1,2	Con2	A_{10}	C_{10}
3,4	Con3	A_{11}	C_{11}
3,4	Con4	A_{12}	C_{12}

Now that all 24 individual inputs have been assigned symbols, the task of expressing in Boolean form the philosophical and engineering constraints can be accomplished.

2. BOOLEAN EXPRESSIONS FOR THE COMPUTER PROPER

The design will be divided into separate entities and simply integrated at its completion. Although this approach leaves much to be desired from a hardware point of view, it was not a primary objective of this effort to reduce the number of essential blocks to a minimum, but more important to provide proof of feasibility of the concept. The division into entities resolves itself quite simply to the following.

There are five modes of operation (NORMAL, EMERGENCY, FIRE 1, FIRE 2, and OVERHEAT). Each one has a separate position on the selector switch of the crew-member's console. Each system is continuously monitored for FAIL and can be positively checked for FIRE or OVERHEAT by a forcing function or push-to-test switch. Readouts available for each of the five switch positions are FIRE, OVERHEAT, OK, and FAIL and apply as previously outlined. Redundancy is provided in the computer by duplicating major blocks of functions and analyzing them. For clarity all references will use the complete computer block diagram, Figure 15. Duplicated blocks are paired as follows: Part A and Part B, Part E and Part F, and Part H and Part I. The discussion of design criteria for each of the five modes follows.

a. Normal Mode (N)

In this mode, a redundancy concept is used to provide a FIRE indication. This indication can occur only if the following set of circumstances prevail:

(1) There is a fire signal from at least two detectors with the same field or a mutual field of view

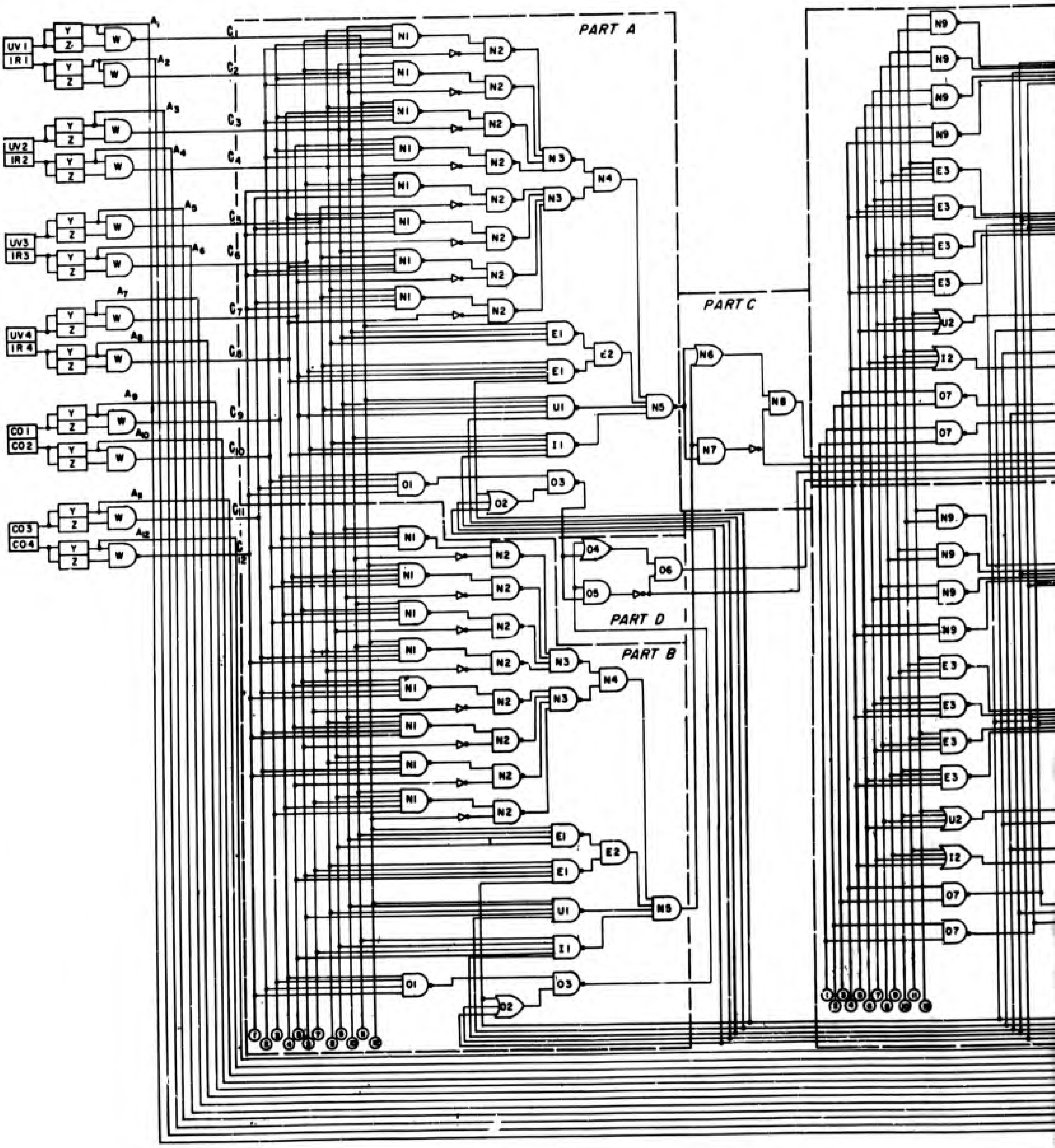
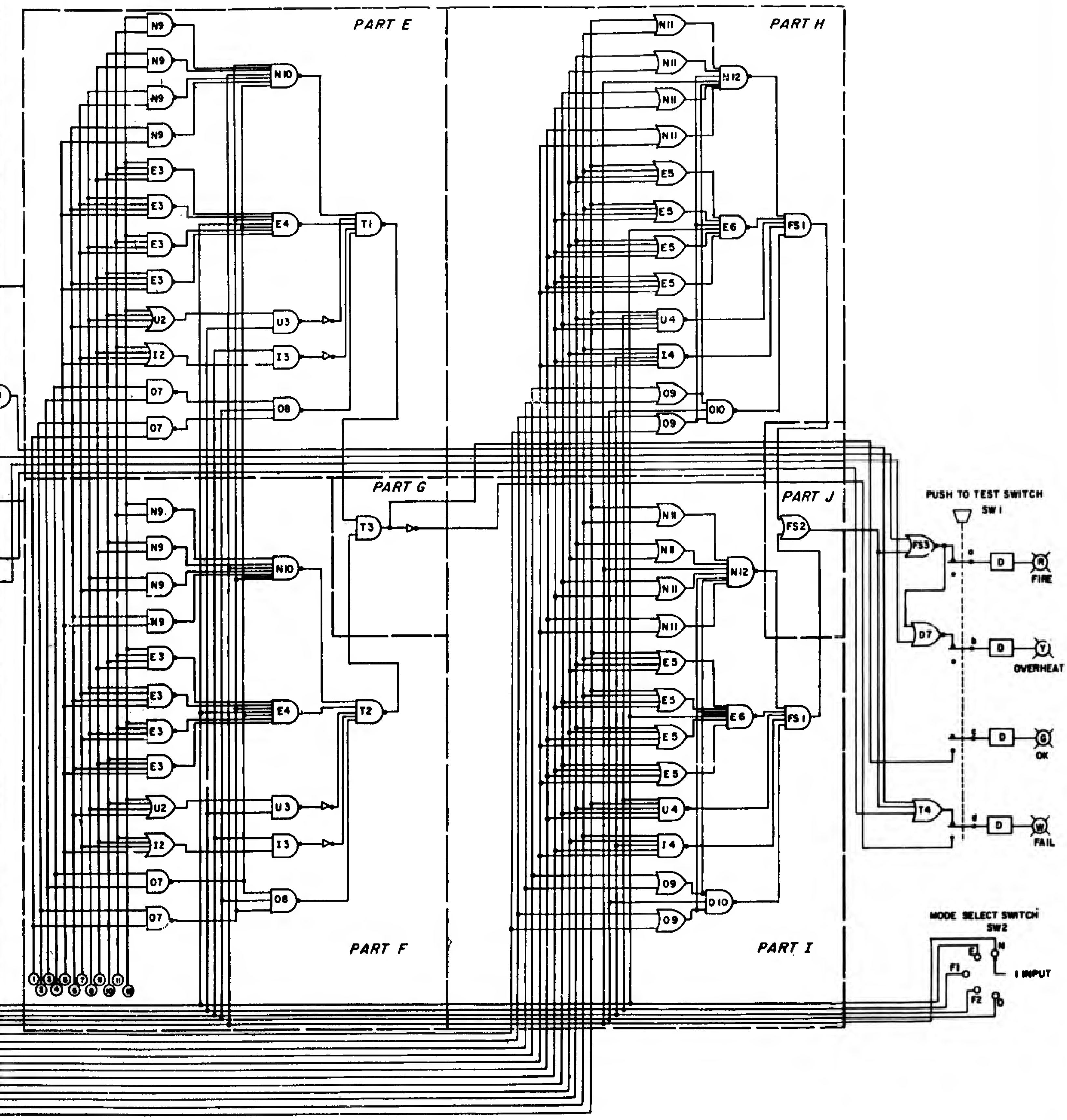


Figure 15. Microcircuit Computer for



Microcircuit Computer for Fire and Overheat Detection

(2) A system failure is not present

(3) The push-to-test switch is not depressed. The logic for determining fire only without any other constraints is shown in following equation.

$$
\begin{aligned}
\mathrm{FIRE}_N = {} & C_1\,(C_2 + C_9 + C_{10} + C_3 + C_4 + C_5 + C_6) \\
& + C_2\,(C_1 + C_9 + C_{10} + C_3 + C_4 + C_5 + C_6) \\
& + C_3\,(C_1 + C_2 + C_9 + C_{10} + C_4 + C_7 + C_8) \\
& + C_4\,(C_1 + C_2 + C_9 + C_{10} + C_3 + C_7 + C_8) \\
& + C_5\,(C_1 + C_2 + C_{11} + C_{12} + C_6 + C_7 + C_8) \\
& + C_6\,(C_1 + C_2 + C_{11} + C_{12} + C_5 + C_7 + C_8) \\
& + C_7\,(C_3 + C_4 + C_5 + C_6 + C_{11} + C_{12} + C_8) \\
& + C_8\,(C_3 + C_4 + C_5 + C_6 + C_{11} + C_{12} + C_7)
\end{aligned}
$$

By analysis this formula states that a FIRE indication will be obtained while on the NORMAL switch position when typically C_1 and C_2 or C_1 and C_9 or C_1 and C_{10}, etc., detect and verify a fire. There are many obvious duplications in this formula and eliminating these duplications results in the following equation:

$$
\begin{aligned}
\mathrm{FIRE}_N = {} & \bar{C}_1\,(\bar{C}_2 + \bar{C}_4 + \bar{C}_6 + \bar{C}_9 + \bar{C}_{10}) + \bar{C}_2\,(\bar{C}_3 + \bar{C}_6 + \bar{C}_9 + \bar{C}_{10}) \\
& + \bar{C}_3\,(\bar{C}_8 + \bar{C}_1 + \bar{C}_4 + \bar{C}_9 + \bar{C}_{10}) + \bar{C}_4\,(\bar{C}_2 + \bar{C}_7 + \bar{C}_9 + \bar{C}_{10}) \\
& + \bar{C}_5\,(\bar{C}_1 + \bar{C}_2 + \bar{C}_6 + \bar{C}_{11} + \bar{C}_{12}) + \bar{C}_6\,(\bar{C}_7 + \bar{C}_8 + \bar{C}_{11} + \bar{C}_{12}) \\
& + \bar{C}_7\,(\bar{C}_3 + \bar{C}_5 + \bar{C}_8 + \bar{C}_{11} + \bar{C}_{12}) + \bar{C}_8\,(\bar{C}_4 + \bar{C}_5 + \bar{C}_{11} + \bar{C}_{12})
\end{aligned}
$$

The first of the two equations assumes a 1 input whereas there really is a 0 input or a $\bar{1}$. The second equation reflects a $\bar{1}$ requirement so that a 0 input means FIRE.

A more practical form of the equation for fabrication purposes is as follows:

$$
\begin{aligned}
& \overline{\overline{\overline{C_1}\;\overline{(C_2\,C_4\,C_6\,C_9\,C_{10})}}\;\;\overline{\overline{C_2}\;\overline{(C_3\,C_6\,C_9\,C_{10})}}} \\
\times\; & \overline{\overline{\overline{C_3}\;\overline{(C_1\,C_4\,C_8\,C_9\,C_{10})}}\;\;\overline{\overline{C_4}\;\overline{(C_2\,C_7\,C_9\,C_{10})}}} \\
\times\; & \overline{\overline{\overline{C_5}\;\overline{(C_1\,C_2\,C_6\,C_{11}\,C_{12})}}\;\;\overline{\overline{C_6}\;\overline{(C_7\,C_8\,C_{11}\,C_{12})}}} \\
\times\; & \overline{\overline{\overline{C_7}\;\overline{(C_3\,C_5\,C_8\,C_{11}\,C_{12})}}\;\;\overline{\overline{C_8}\;\overline{(C_4\,C_5\,C_{11}\,C_{12})}}} \\
& = \mathrm{FIRE}_N = 1
\end{aligned}
$$

TABLE IV

COMBINATIONS OF SENSORS TO DETECT AND VERIFY FIRE OVERHEAT IN THE NORMAL MODE

Detect	Verify												Total Combinations
	UV1	UV2	UV3	UV4	IR1	IR2	IR3	IR4	C1	C2	C3	C4	
UV1		F	F		F	F	F		F	F			7
UV2	F			F	F	F		F	F	F			6
UV3	F			F	F		F	F			F	F	6
UV4		F	F			F	F	F			F	F	5
IR1	F	F	F			F	F		F	F			4
IR2	F	F		F	F			F	F	F			3
IR3	F		F	F	F			F			F	F	3
IR4		F	F	F		F	F				F	F	2
C1										O			1
C2									O				1
C3												O	1
C4											O		1
F = fire O = overheat													40

b. EMERGENCY Mode (E)

To detect a fire in the E mode requires any single sensor to be allowed to detect the fire and verification is not required. The equation for detecting fire is

$$\overline{C_1 \; C_2 \; C_3 \; C_4 \; C_5 \; C_6 \; C_7 \; C_8 \; C_9 \; C_{10}} = 1 = \text{FIRE}$$

The detection of an overheat is identical to that in the NORMAL system given previously. Fire detection in this mode is performed by E1 and E2 in Part A. An input to N5 provides the appropriate signal to the comparator, Part C.

The failure of four radiation sensors, two adjacent housings, or two overheat sensors in the same zone constitutes a system FAIL. The equation takes the following form:

$$\overline{(A_1 + A_2 + A_3 + A_4)\;(A_1 + A_2 + A_5 + A_6)\;(A_3 + A_4 + A_7 + A_8)\;(A_5 + A_6 + A_7 + A_8)}$$

$$\overline{(A_9 + A_{10})\;(A_{11} + A_{12})} = 1 = \text{FAIL}$$

Blocks E5 and E6 (Part H) provide input into FS1. If a failure occurs, E6 puts out a 1 which causes FS1 to put out a 1 or a FAIL signal to FS2 the OR gate. The reaction is then identical to the NORMAL system.

A push-to-test system requires that the system is operational as a whole and that numerous sensors can fail and not be of any problem. The equation for push-to-test failure is as follows:

$$\overline{\overline{C_1 \; C_2 \; C_3 \; C_4}\;\;\overline{C_5 \; C_6 \; C_7 \; C_8}\;\;\overline{C_9 \; C_{10}}\;\;\overline{C_{11} \;\; C_{12}}\;\;\overline{C_1 \; C_2 \; C_5 \; C_6}\;\;\overline{C_3 \; C_4 \; C_7 \; C_8}} = \text{FAIL} = 1$$

In Part E, E3 and E4 perform the basic function of the above equation. A 1 output from E4 results in a FAIL output of a 1 to T1.

c. FIRE Mode (F1) — Ultraviolet System

Switch SW2, Position 3, the F1 mode, is to engage the ultraviolet radiation detection system. When this system is operating, a single ultraviolet detector can detect a fire, and a single sensor failure will be read out. For fire detection, the following equation holds true:

$$\overline{C_1 \; C_3 \; C_5 \; C_7} = \text{FIRE} = 1$$

This function is performed by U1 and its output is to N5 (Part A). No overheat detection is possible in this mode, only fire detection. During normal operation, the FAIL light would be activated using the following logic if a failure occurred in any of the sensors:

$$\overline{A_1 \; A_3 \; A_5 \; A_7} = \text{FAIL} = 1$$

Block U4 Part H performs this task. The push-to-test logic is also simple and is as follows:

$$C_1 + C_3 + C_5 + C_7 = \text{FAIL} = 1$$

Thus if UV, or UV3 or UV5 or UV7 fail, a 1 will be input to U2 and in turn to U3, Part E. U3 must be turned on by switch position F1 so that a NAND can be used. The inverter after the NAND allows for NAND circuitry instead of AND circuitry.

d. FIRE Mode (F2) — Infrared System

The fourth position on SW2 is to activate the infrared fire detection system. As with the ultraviolet system, overheat detection is not possible in this mode. The output from SW2 is a 1 which activates only the F2 system. A fire can be detected if the same logic is used for infrared as was used with the ultraviolet system. Its form is

$$\overline{C_2 \; C_4 \; C_6 \; C_8} = \text{FIRE} = 1$$

and it is performed by I, Part A. The failure logic likewise is identical for a sensor failure in both the ultraviolet and infrared mode and is as follows:

$$\overline{A_2 \; A_4 \; A_6 \; A_8} = \text{FAIL} = 1$$

Block I4, Part H, performs this requirement. The push-to-test to read FAIL is

$$C_2 + C_4 + C_6 + C_8 = \text{FAIL} = 1$$

This function is provided by I2 and I3 Part E.

e. OVERHEAT Mode (0) — Continuous Sensors

With SW2 in Position 5 only, the overheat system using the continuous sensors can be used. Fire detection cannot be made by any direct means using this system. The equation for overheat detection is as follows:

$$\overline{C_9 \; C_{10} \; C_{11} \; C_{12}} = \text{OVERHEAT} = 1$$

Blocks 01, 02, and 03 Part A perform the function. A FAIL during normal operation requires both detectors in one zone to fail as indicated below:

$$(A_9 + A_{10})\,(A_{11} + A_{12}) = \text{FAIL} = 1$$

Blocks 09 and 010 provide this requirement in Part H.

The final push-to-test function for the computer is provided by 07 and 08 Part E and is defined by the following equation:

$$\overline{\overline{A_9}\;\overline{A_{10}}\;\;\overline{A_{11} \; A_{12}}} = \text{FAIL} = 1$$

3. CONCLUSIONS

Although the basic requirements for the computer have been defined, there are other functions that provide for fail-safe and the readouts that require analysis.

The comparators Part C and Part D have previously been analyzed, but Part G and Part J have not.

Part G comprised of an AND gate and inverter provides the FAIL, OK signal from Part E and Part F. Part E and Part F are basically the push-to-test function of the computer. If both Parts E and F put a 1 into the AND gate T3, a 1 will come out to T3 and light the OK light. The concept of $\overline{\text{FAIL}}$ is used for OK. If either Part E or Part F does not cause a 1 input into T3, a 0 will go to the OK light which will not light it, and the inverter after T3 will send a 1 to activate the FAIL light. Obviously if both E and F indicate a FAIL, a 0, the FAIL light will be activated and the OK light will not. It must be remembered that this is a push-to-test function whose fundamental job it is to detect a system failure so that false warnings cannot go undetected during routine operation.

Part J, an OR gate labeled FS2, is the fail-safe gate that provides a FAIL light during routine operation. Part H and Part I detect directly and continuously any failure of a sensor during routine operation. Since FAIL is of maximum importance, a failure signal from either H or I must activate the FAIL light. Thus a 1 from either of the FS1's will be input to FS2 and transferred as a 1 to both FS3 for FIRE and T4 for FAIL. A 1 at FS3 provides a 0 or nonactivating signal to the FIRE light. The T4 OR gate, however, transfers the 1 to the FAIL light which turns it on. The only signal that will provide FIRE is a 0 output from both FS1's.

The circuit elements FS3, D7, and T4 are the precedence circuits. The order of precedence was previously established as FAIL, FIRE, and OVERHEAT. As shown in the preceding paragraphs, FAIL takes precedence over FIRE. Now the precedence circuit for FIRE over OVERHEAT will be shown. If D7 receives a 0 from Part D, there must be a 0 input from FS3 in order to provide a 1, or activating signal to the driver of the OVERHEAT light. If overheat occurs and then a fire, the output from FS3 will be a 1 input to D7 which will not allow the OVERHEAT light to be activated. Thus the precedence of FIRE over OVERHEAT is established.

The equations describing the push-to-test function of the fire systems N, E, F1, F2, and 0 state only that a FAIL indication will be given. When a FAIL indication does not occur, a $\overline{\text{FAIL}}$ condition does. A $\overline{\text{FAIL}}$ is by definition OK, and so the OK light is activated.

SECTION V

READOUT DESIGN

The readout must provide the following basic capabilities to satisfy a crew member that he has a good system for fire or overheat detection. First and foremost it must attract the pilot's attention without being a completely distracting influence during critical maneuvers. When the readout is placed in the immediate field of view, the shape, color, and contrast can be determined. Secondly, the readout must be simple and not provide mutually exclusive information such as FIRE and OK simultaneously thus requiring the pilot to determine whether this means he had a fire and it's out or that the computer is OK and there is FIRE. Finally the readout must conform to the requirements for all readouts in aircraft such as reliability, ease of maintenance, etc.

Since it is the prime goal of this effort to reduce false warnings, it is important to provide this capability physically in the design of the readout.

The use of two lamps instead of one where only one will operate at a time provides bulb fail-safing. When the primary bulb fails, a transistor switches in the second bulb. A sort of a monostable flip flop can be used to do this very nicely. Although it is not the goal of this effort to design a flyable readout, these guidelines will provide a firm basis for doing so. Both lamps should be easily replaceable by removing the readout, Figures 16 and 17, or by unscrewing the bulb from the front, Figure 18. When the primary bulb fails, the secondary bulb should provide that bit of additional information to crew members during checkout. A small fiber optics rod or equivalent inserted next to the bulb would provide an illumination next to the bulb, Figure 19, and could be used to locate an inoperative primary bulb. If all the bulbs on the right of the readout of Figure 18 were used and a bulb test for primary bulb were used, the "light pipe" located next to the bulb would evidence the failure. Other fundamental requirements are light-weight and low power consumption. The setup in Figure 18 could be made using electro-luminescent panels to reduce both size and weight, but they would not necessarily provide the required redundancy. Actually a simple rear-lighted display was built and tested with satisfactory results in the laboratory (Figure 17).

For a typical eight-engine jet aircraft, the units could be strung across the top of the flight panel in tandem with the selector switch for the five modes centrally located so that either the pilot or copilot could use it (Figure 19). The rotary switch could even in itself be the push-to-test switch. This would reduce weight and make it somewhat easier to install due to its lack of bulk. The selector switch should be available for each computer so that the E, F1, F2, and 0 switch selection during flight for a failed computer need not switch other computers out of their best operating mode.

An important point should be brought out regarding bulb failures. The lack of a push-to-test button for each of the bulbs is an asset and in no way detracts from the systems capability. In fact since it is necessary to indicate whether all bulbs are OK, an automatic lock-on of all the indicator lights can be provided.

Figure 16. Rear Projection Readout

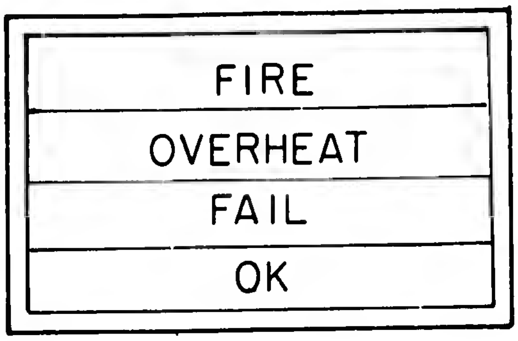


Figure 17. Rear-Lighted Readout

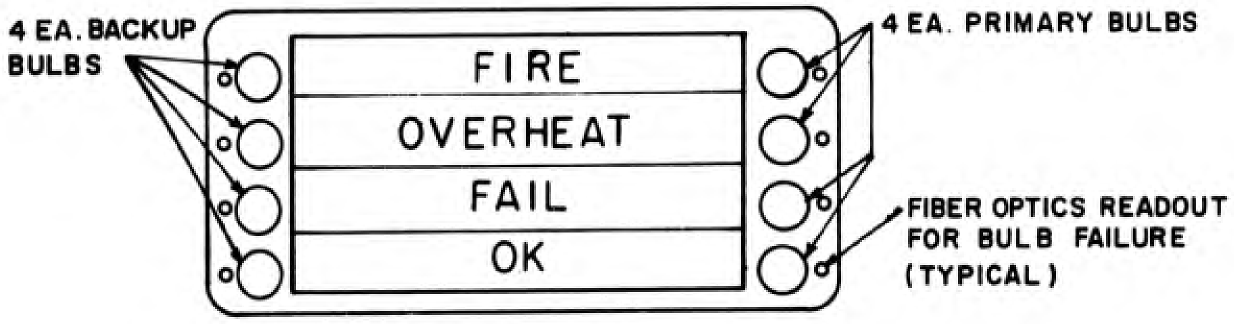


Figure 18. Front Projection Readout

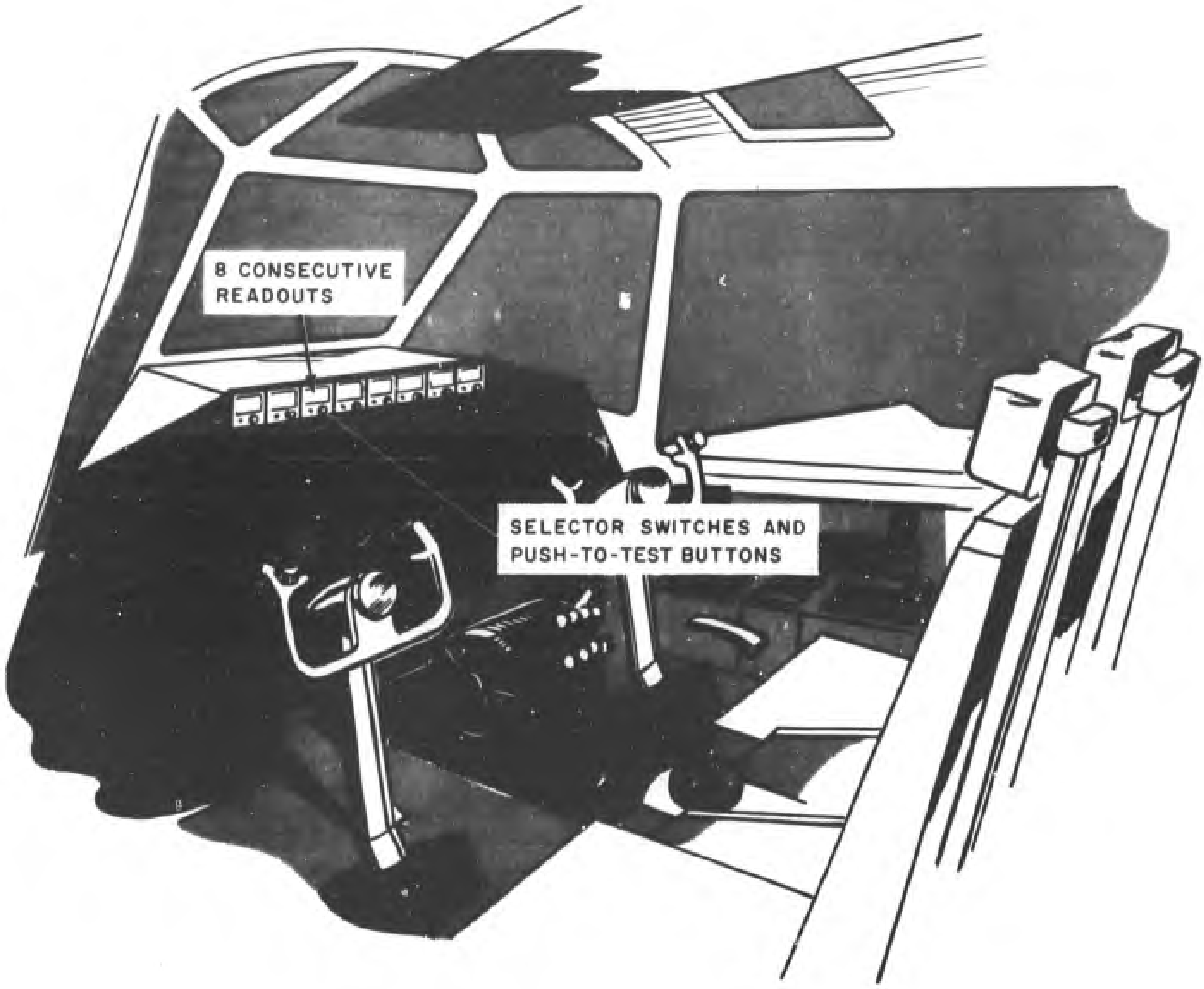


Figure 19. Cockpit Display

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. GENERAL

The computer, being a first-generation device, can be expected to grow and mature into a more sophisticated concept. No attempt has been made to add the necessary time delay circuits or thoroughly define tautology for this application. Fanouts to respective blocks have been kept within reason, but vary depending upon which manufacturer's microcircuit devices are used. To build the computer as designed requires a series of chips with adequate power to drive seven follow-on devices. If the computer is designed around a particular manufacturer's type of microcircuits, the following specifications should be within the realm of practicality:

a. Size - 1/2" x 2" x 5"

b. Weight - 6 oz

c. Response time - 1 microsecond or less

d. Capability to withstand g forces and vibration associated with Mach 3 aircraft

e. Temperature capability of -65°F to +125°C

f. Power consumption below 1 watt

g. Self-checking fail safe

h. Failure rate of less than one for every 200,000 aircraft engine hours (system failure rate for nonfail safe failure)

i. Capability to interrogate 12 sensors on a continuous fail-safe basis

j. Capability to drive readout devices directly

Size and weight reductions can be made as large scale integrated circuits become available. Present yields of large scale attempts that could make this computer on a single chip have proven economically unfeasible.

Temperature limitations of silicon devices could also be considerably improved by using silicon carbide. Silicon carbide microcircuit technology is in the future and, even though it could conceivably be used at 1000°F, its development would be expensive and time-consuming.

2. CONCLUSIONS

The computer can substantially improve aircraft hazards detection. The direct benefits are as follows:

a. Less down time, more flight-ready aircraft

b. The virtual elimination of fuel dumping and aborted missions due to false alarms

c. The ability to truly differentiate between the class of hazard, that is, either fire or overheat

d. Increased pilot and crew member confidence in flight systems so that attention can be paid to critical duties

e. Increased human response time due to the knowledge that a hazard truly does exist when the FIRE or OVERHEAT lights are activated

f. Increased total capability of fire detection when one system or part of a system fails

Other benefits can be derived by applying the computer to particular situations, such as using one computer on all types of aircraft to determine computer failure rates and the maximum reliability. The fact that the computer was designed to be used on any type of jet aircraft up to Mach 3 in particular allows a cost savings to be made by large quantity purchases. A simple simulator can be used to check out the computer so that it can be adequately qualified at the laboratory level for flight use. The result of this is that ultraviolet, infrared, and continuous type (overheat) sensors can also be more exactly specified in their output voltages and modes thus making it possible for the first time to perform simulated testing with a basic fiducial.[2]

3. RECOMMENDATIONS

For Mach 3 aircraft and above use, it is recommended that simple, high-temperature, signal-processing sensing heads with radiation sensing detectors be developed and flight-tested prior to the final computer design. New signal processing trinary coding may evolve causing a major redesign of input signal conditioning electronics. Design constraints from a legislative point of view should be determined, and multiplexing of computers to reduce weight should be accomplished.

Future systems for flight vehicle use, including spacecraft, should provide homeostasis monitoring capability. For instance not only should fire, explosion, and overheat be monitored, but synonymous occurrences such as loss of pressure in hydraulic lines and fire should be monitored and provide the appropriate readout. Thus all available sensors could be used to give quantitative and qualitative data so that more information is available to crew members. Supplemental sensors could be added to give total protection. With the use of this approach, an alpha-numeric readout capable of presenting a large number of combinations should be designed. In total the implication of not adopting a computer system for both manned aircraft and manned spacecraft is ominous. Present hardware, as good as it is, cannot on an individual basis be expected to supply either the reliability or the capability required for advanced vehicles. Industry has not caught up in the area of total hazards monitoring due to its newly generated need. It is, therefore, the responsibility of each individual associated with the increments of the hazards problem to generate the requirements for his own computer to provide the capabilities required.

[2] A fiducial is a measurement reference to which all measurements taken can be referred.

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APPENDIX

ILLUSTRATIONS OF BREADBOARD MODEL DESIGN

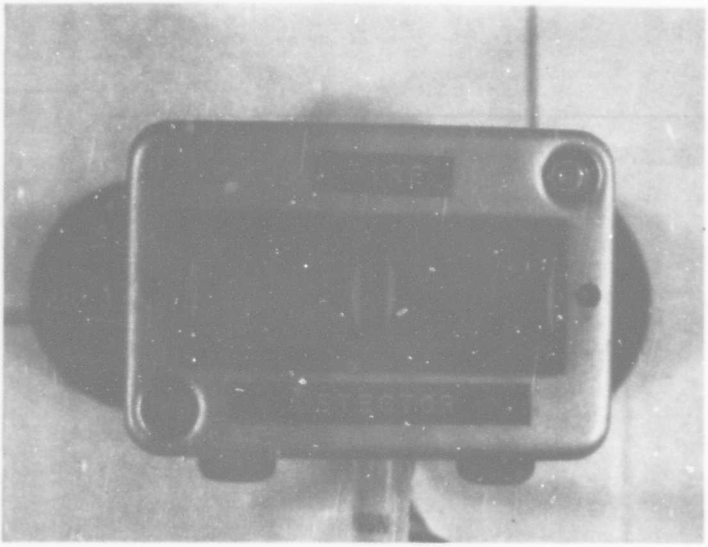

Figure 20. Prototype Readout

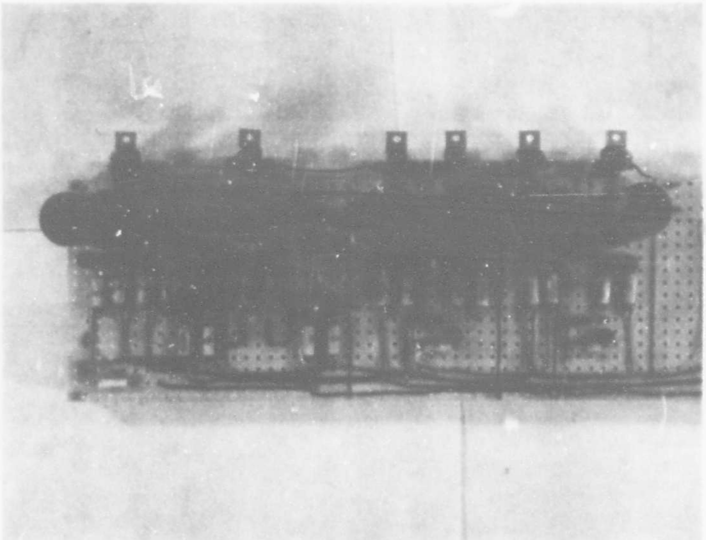

Figure 21. Breadboard Model of Computer

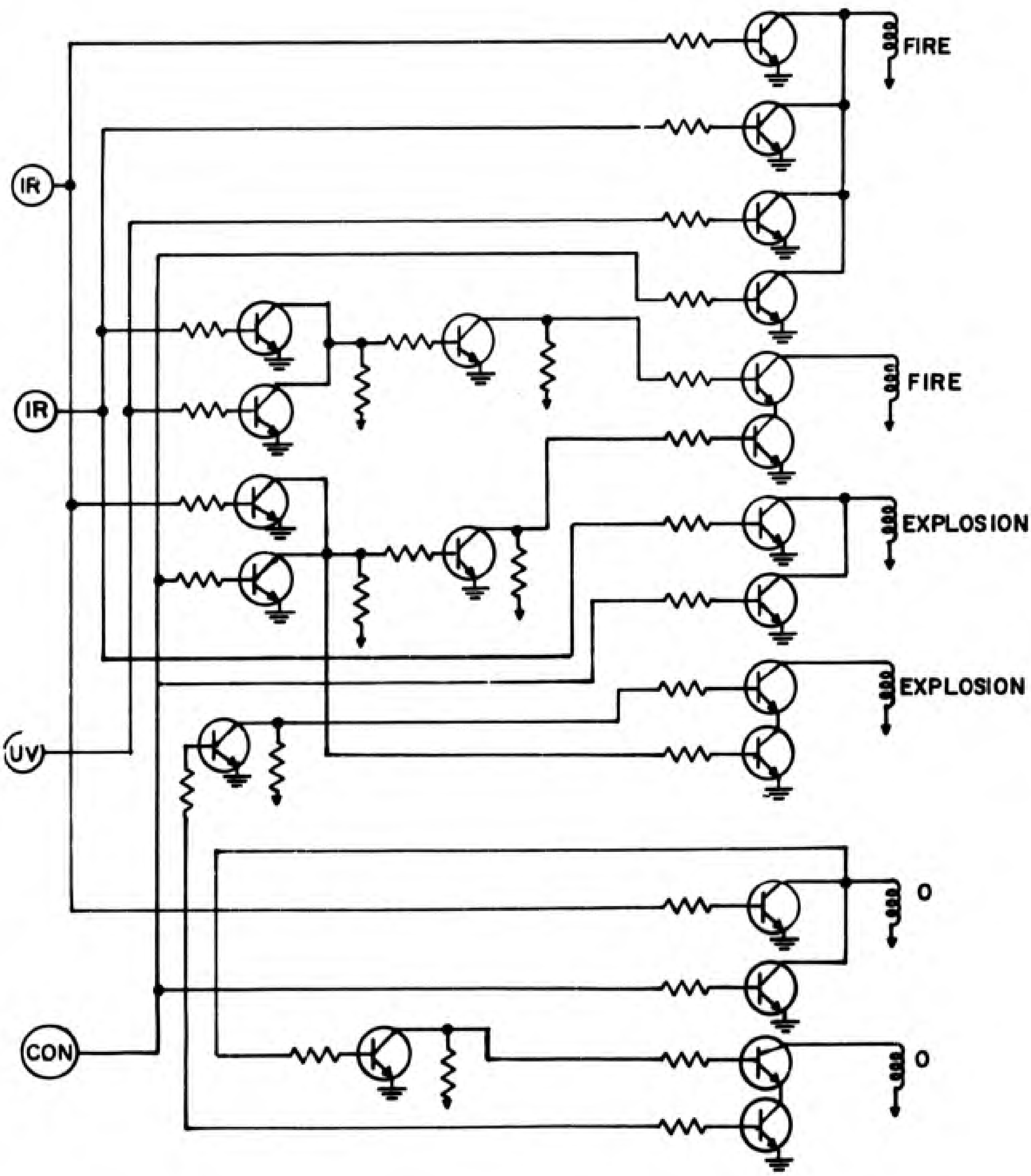

Figure 22. Schematic of Breadboard Model of Computer

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13. ABSTRACT

This report describes the design of a computer for use in a unique integrated system for detecting fire and overheat in aircraft engine nacelles. This system uses ultraviolet and infrared sensors for fire detection, continuous elements for overheat detection, and the newly designed microcircuit computer for sensor analysis. The computer, operating in any of five modes — Normal, Emergency, Ultraviolet, Infrared, or Continuous — activates a specially designed alpha-numeric readout.

Computer design criteria are firmly established, and the finalized two-channel, fail-safe, self-checking computer design is described. Boolean equations and a final schematic for the computer are given. Finally, the limitations of applying the computer from both an engineering and a legislative point of view are specified. A final flight-qualified microcircuit computer weighing 6 ounces or less, 1/2" by 2" by 5" in size, and drawing less than 1 watt of power can be built using the basic computer design formulated.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Computer Fire Detection Overheat Detection Microcircuit Computer Hazards Detection						

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