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COMBUSTOR FLAME SENSOR WITH HIGH TEMPERATURE ELECTRONICS

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ABSTRACT

A high temperature solid state turbine flame sensor has been developed and is being tested for eventual use as a combustor performance sensor. It directly senses only the flame deep ultraviolet without any response to hot component infrared energy (>700 nanometers); the dynamic range is large; and the response time is fast enough for combustor control, i.e., less than 200 milliseconds.

The sensor electronics operate up to 250°C and some detector performance data has been taken as high as 540°C as described by Cusack et al (1994). The design uses recently available SiC electronic components, other components specially tested for the application, and proprietary techniques of electronic component packaging. Specific experience in packaging turbine engine optical and temperature sensors is necessary for this unique high temperature electronic technology.

A test program for discrete components indicates what elements are available for this temperature range and prototype sensor data from both laboratory qualification tests and engine performance tests verify the design.

INTRODUCTION

A new turbine engine combustor optical flame sensor is described that provides a better sensor than currently available. This sensor is applicable to the system described by Brown's and Gorowitz's patent (1993). It has high temperature electronics and analog output, both of which enable the sensor to be used in current and next generation gas turbines. The sensor measures the ultraviolet (UV) emissions from a flame without ambiguity from hot metal component emissions. Output is an analog signal which represents the amount of UV detected from a defined location. All components within the sensor operate to 275°C without ancillary cooling.

This paper describes the prototype and production models which have been used in design assurance laboratory and field tests. The general problem of sensing combustor flame spectrum is discussed, some prototype sensor field test results, data from the high temperature electronic component testing, and finally data from the sensor lab tests are presented.

EXISTING TECHNOLOGY

One commonly used optical flame sensor type uses a gas discharge tube detector with UV sensitivity from about 200 to 270 nanometers. One advantage to it is that there is intrinsic photoelectron gain. Some tube detector designs can operate at temperatures to about 200°C. It requires at least some passive electronic components at the sensor: resistor(s) and in some models inductance as well. Many consider a disadvantage the fact that a high excitation voltage is necessary, usually 300V. This requirement means a dedicated power supply and signal processing circuit, and long runs of high voltage wire.

Another flame sensor style uses a standard silicon detector circuit and temporally filters the resulting signal, using only the AC component(s) to recognize a flame. The electronic components must either be cooled or installed away from the hot environment with a high temperature optical head and fiber optic cable on the engine. A fiber optic link offers more surfaces to be contaminated. Another potential disadvantage is that response time for the sensors is longer than the desired 200 milliseconds because of the AC signal processing.

FLAME UV SIGNAL

The UV emission from a flame consists of spectral lines from some of the chemical reactions combined with broad band thermal emissions from the hot gas materials. There are emission measurements published (Sneider and Spaberg, 1989; Linford and Dillow, 1977) and unpublished using different fuels used in turbine engines; they all shown a similar pattern. In a combustor there are other optical signals which are not a function of flame presence or behavior, mostly from hot metal or ceramic coated metal liner walls. Typical spectra are shown in Figure 1 where the flame signal

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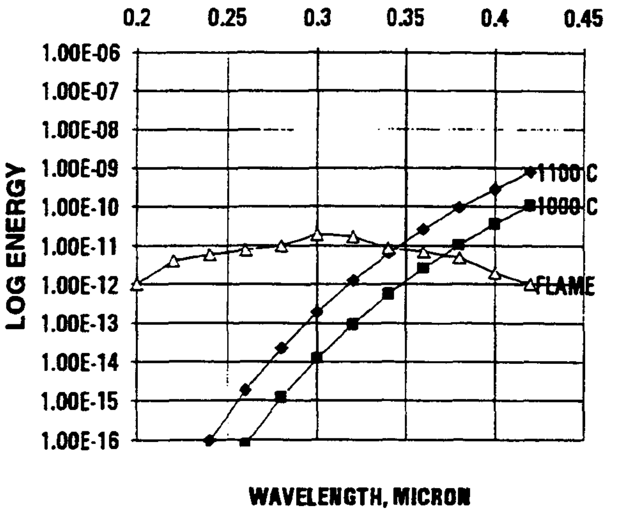

FIGURE 1. FLAME UV AND WALL IR EMISSIONS

is compared to signals from equivalent sized areas of hot metal at 1000°C and 1100°C.

The sensor receives the flame UV energy through some inlet aperture, then it is directed through some solid angle (f number) to the detector of limited size. The flame size is limited, as well. Figure 2 schematically shows the optical arrangements which dictate how much electrical signal is generated. The signal is proportional to inlet aperture area and is a strong function of the solid angle.

SENSOR OUTPUT

The optical signal reaches a silicon carbide (SiC) UV sensitive photodiode which absorbs the spectrum between 200 to 400 nanometers and yields an electrical current proportional to total energy absorbed. The current signal is very small. Even with a generous aperture of 25 millimeters it can be less than 1 nanoamp for a reasonable size (cost) SiC photodetector. As a result, the signal amplifier must have very low offset current and leakage current. A pair of SiC transistors are used differentially to provide a very low leakage current preamplifier. Following that is a high temperature silicon based amplifier tested to 300°C. The general circuit schematic is shown in Figure 3.

The detector, amplifier feedback resistor, and amplifier input impedances are all very high, so the circuit node common to them must be kept generally larger than 10 gigohms from ground potential for the circuit to perform effectively. For this reason these components and the current paths between are hermetically sealed in the sensor. The amplifier operates from a single sided supply and provides an analog output from about 0.5 volts to 5 volts. The output is linear with the input UV energy from the flame and is considered an indicator of flame temperature.

ENVIRONMENTAL SPECIFICATIONS

The environment at the power generation turbine combustor where flame sensing is performed is severe for an optical instrument. It does depend upon the exact engine model and its installation conditions, but in general the temperatures are higher than standard electronics can withstand and vibration resistance requires particular attention to mechanical packaging design. Other environmental conditions include: humidity, fluid compatibility with fuels, oils, and washing compounds, explosion proof ability, temperature shock, etc. Before the sensor was considered

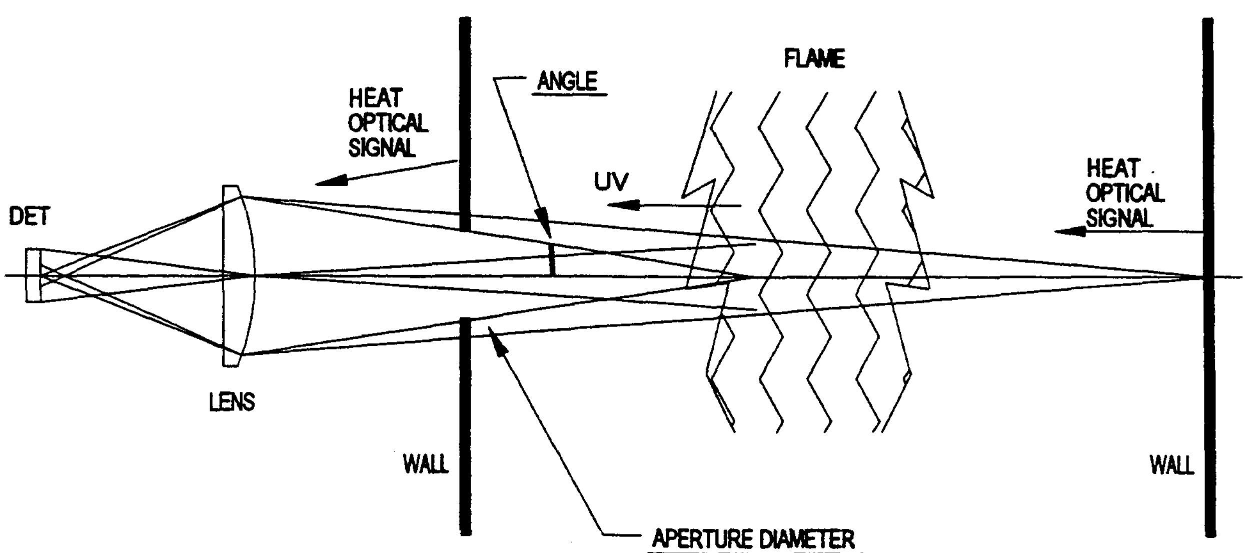

FIGURE 2. FLAME SIGNAL AND HEAT SIGNALS

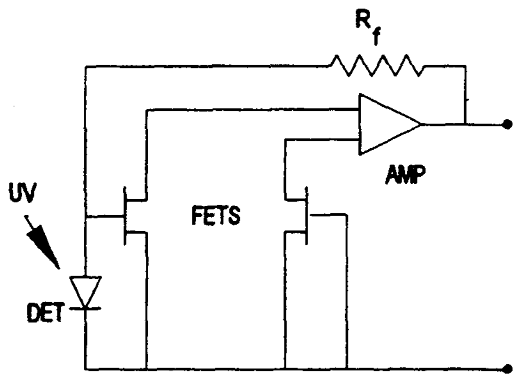

FIGURE 3. BASIC CIRCUIT ELEMENTS

ready for wide field application it was subjected to a series of design assurance tests that subject the design to actual engine environment. The UL specification 1203 (Explosion-Proof and Dust-Ignition-Proof Electrical Equipment) is being used as a criteria for the instrument and a third party vendor will perform final qualification tests to that standard.

For temperatures, the engine surface environment is assumed from -55°C to 400°C. The immediately surrounding air is assumed from the same minimum to 175°C maximum and it is assumed that there is active air ventilation from an outside air temperature up to 50°C. The air velocity is taken to be 1.5 meters/second. These conditions lead to a -55°C to 260°C temperature environment specification for the instrument's continuous operating temperature range.

The vibration environment is highly dependent upon local mounting geometry. In general, the land based turbine vibration environment is less severe than the aircraft engine cases. In some aircraft engine mounted components vibration resistance to 60 g's is required. The land based turbine engine requirements are as low as 4 g's, from 10 to 1000 Hz. Field measurements have shown, however, that nearly 10 g's can be expected on engine surfaces such as ducts where flexing is allowed. This can be considered a maximum on combustor cans which are more compact than, for example, exhaust ducts. Further, because the flame and hot gas are at their most energetic state, acoustic energy is a potential severe threat, as well.

HIGH TEMPERATURE COMPONENTS

For this project a number of components have been evaluated for operation to 300°C temperatures. They include detectors, transistors, several types of integrated operational amplifier, and resistors. All have been used in the field test units. Information to assist in component selections is available from many sources such as Tomana et al (1992).

Silicon zener diodes have been evaluated for operation up to 300°C. Three each of two types of 500mW hermetically sealed glass silicon zener diodes, 1N758A and 1N965B, were chosen from two different manufacturers. The devices are rated at Tj max of 200°C. A current/voltage test was run on each diode at 20°C, 200°C and 300°C. The 1N758A (nominal 10 V) showed a 16% increase at 300°C and the 1N965B (nominal 15 V) showed a 17% increase at 300°C. The specification for normal temperatures ranges allows approximately 27% change for a 275°C change. The Figure 4 graph shows good performance over the range of .1mA to 10mA. The test samples are presently in life test at 300°C at a bias of 3mA, and have shown essentially no change.

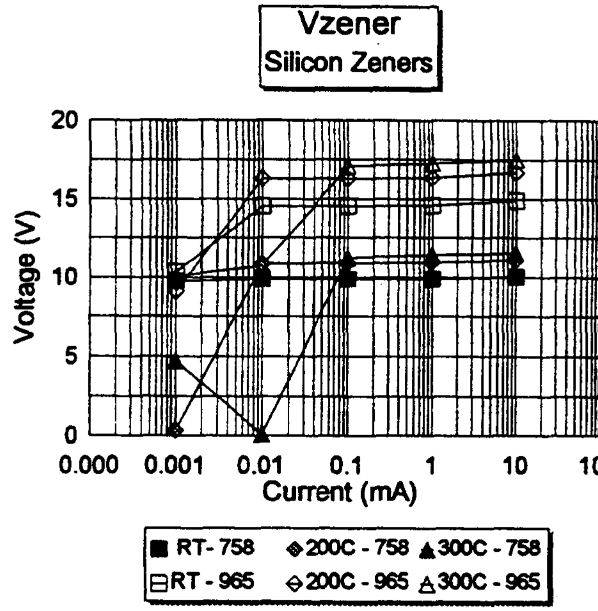

FIGURE 4. ZENER DIODE BEHAVIOR

Since SiC LEDs are commercially available, the devices were tested to determine their suitability as a high temperature substitute for a voltage regulator/zener. The device would be used in the forward mode, not as a true zener. It is recognized that the knee would not be sharp, but the function could still be useful as a regulator. We optained samples of two types of LED die. The D10 is 10 x 10 mils and the D8 is 8 x 8 mils. Six of each device were mounted on a header and the lids sealed. Voltage/current tests were conducted on each die at 20°C, 200°C, and 300°C. At 10mA the forward voltage of the die was roughly 2.5V for the D10 and 3V for the D8. As expected, regulation of the D10 was better than the D8; the internal impedance of the larger device should be less. Forward voltage change was approximately -16% for the 275°C change from room temp to 300°C. The six die were then connected in series to create a larger "zener" effect. With a bias of about 3mA, the 6 cell ,D10 device provided about a total regulation of +2%,-18% over an input voltage change of +/- 10% and a change of RT to 300°C. The two 6-cell devices are presently in life test at 300°C at a bias of 3mA and have shown no change.

Two types of commercially available axial lead resistors were tested for high temperature performance;a lot of (6) 10k wire wound (WW) resistors type RS2B, and a lot of (6) 1000 Meg metal oxide (MOX) resistors. The RS2B is rated to 350°C and the MOX is rated to 220°C. The temperature coefficient of the MOX is specified at 250ppm/°C up to 125°C, and the RS2B is specifiied at

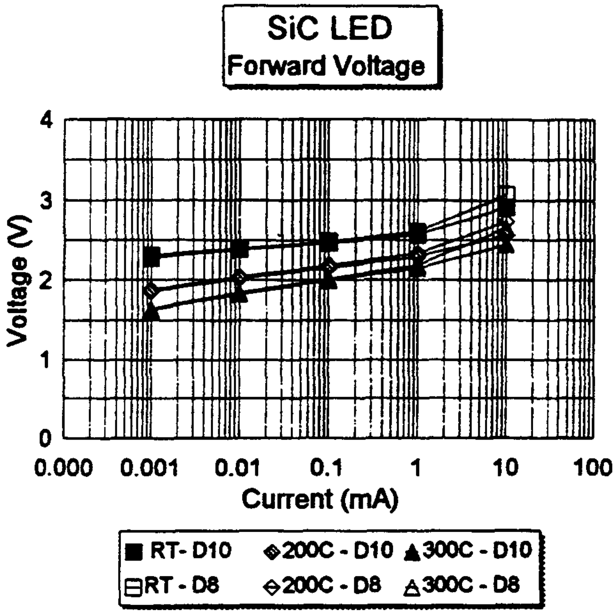

FIGURE 5. LED AS VOLTAGE REGULATOR

20ppm/°C. Therefore the allowable deviation for the 275°C change from RT to 300°C is 7% for the MOX and .6% for the RS2B.

The samples were tested at 1V and 10V, at 20°C ,200°C, and 300°C. A graph on Figure 6 of the average performance of both types was within specification even to the 300°C limits, except for the MOX resistance change with voltage at temperature above 200°C. Voltage variation is almost negligible up to 200°C, but is quite significant at 300°C.

All samples are presently in life test at 300°C at a 12V bias and have shown no measurable changes.

Radiation hardened silicon devices have been viewed as capable of high temperature operation because some of the failure mechanisms are common to high temperature exposure. From our own experience with packaging and testing SiC transistors, the manufacturing details of these silicon operational amplifiers are well suited for high temperature.

Five low power, radiation hardened programmable operational amplifiers have been tested for high temperature suitability. The device is rated to 125°C with junction temp of 175°C max. The device is packaged in a T05 type metal can, the die is attached with gold silicon eutectic alloy. The amplifier is programmable by Iset to allow optimization for use. A basic test was run to determine if the device would survive a 300°C environment. The amplifier was run at +/-15V and +/-5V supply levels. Offset was recorded for low resistance (2K) balanced inputs, this is shown as Vos. Offset was also recorded for an unbalanced condition of 1Meg. This reading was converted to provide an indication of total leakage current, this is shown as Ios+Ib. Initial tests run with Iset of 15uA showed good operation to 200°C, but railed at 300°C. Increasing Iset to 100uA allowed the device to operated sucessfully to 300°C (Input bias current is directly proportional to Iset).

As can be seen on the graph, Figure 7, very good performance was achieved up to 200°C, Vos < 4mv and Ios+Ib < 40nA. Error increased dramatically past 225°C, with 300°C values of Vos of about .25V and total leakage currents of about 500nA. While this performance is not spectacular with respect to op amps currently available to 225°C, it does show promise of use - particularly where the amplifier is used as a gain element within a closed loop. The AC performance was also tested and showed accurate operation to 10Khz (2Vp-p).

The SiC UV photodetectors are commercially available from CREE and their performance has been well documented by various sources such as Gati et al (1994). The transistors used in the electronics were developed and packaged specifically for the new sensor environment. The transistors need to have a very high and

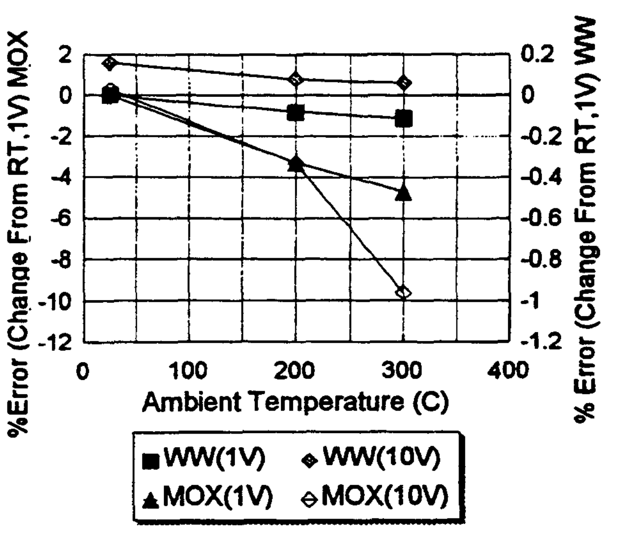

FIGURE 6. RESISTOR BEHAVIOR

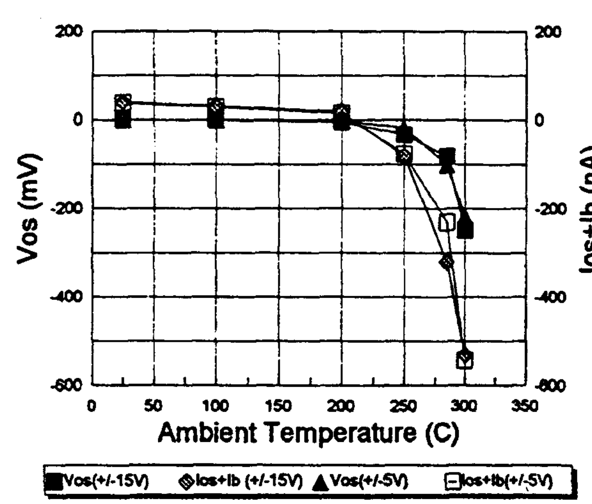

FIGURE 7. OP AMP PERFORMANCE

very well behaved input impedance and their switching behavior needs to be matched between the two. The circuit node where the optical detector, its transistor input, and the circuit feedback resistor meet, is critical. Leakage current is noise, and to measure less than a nanoamp, a leakage current of less than 100 femtoamps is desirable. Also, the gate to source threshold voltages define switching, so they must change together as a function of time and temperature. Components, then, are shown to be useful for the application, applicable to signal processing and power supply connections.

PROTOTYPE SENSOR TEST

Two different types of prototypes have been built with increasing high temperature capability. The first was tested in the field during the spring of 1993 and then again in the summer of 1994. The second style was tested on an instrumented combustor rig early in 1994. A production design cycle is in process with the lessons learned from these field tests and the component evaluations. The design is slated for first build before the end of 1994 and subsequent UL and engine qualification.

In the 1994 field test the prototype flame indication sensor was mounted on a land gas turbine combustor without external cooling to detect the presense or absence of combustor flame. This sensor is shown in Figure 8. The flame sensor was mounted to view the combustion flame axially. The sensor included the SiC optical detector sensitive to ultra-violet radiation from approximately 200 nm to 400 nm and an amplifier to condition the detector photocurrent to a 0 to 10 volt output signal format.

In the test a threshold voltage of 0.2 volts was set to determine whether or not a combustor flame was present. Voltages between 0.2 volts and 10 volts indicated a combustion flame was present during operation. The combustor was cycled "off" and "on" several times as the corresponding flame sensor output signals were monitored. Sensor output signal response times of 200 msec were achieved. During the field test the combustor fuel-to-air ratio and flame ignition temperature were varied, the flame indication sensor provided an analog voltage output that varied with and was proportional to the fuel-to-air ratio and flame ignition temperature in the combustor.

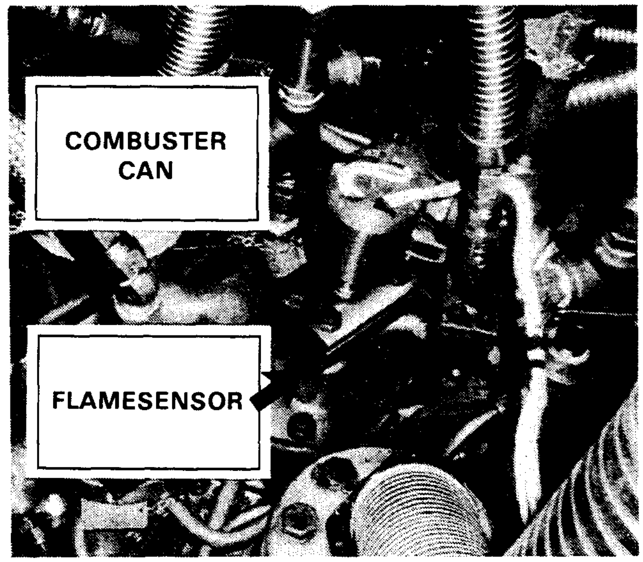

FIGURE 8. SENSOR FIELD TEST

SUMMARY

Electronic components are available for engine accessory operation without cooling. Efforts are underway by many to bring such devices to market. Besides this more robust thermal design which has a lower installation cost, the flame sensor described also has the benefit of an output signal more easily integrated into a combustion control system. It is being qualified to survive the vibration, temperatures, fluid compatibilities, etc.

The field tests of several prototype versions have verified this product's suitability for flame detection. Further work is expected to test its analog flame monitoring capability.

Development of the flame sensor has taken approximately two years to date. The component selections and manufacturing methods are therefore being qualified together for the application. Close involvement with field engines and the user community have provided essential feedback for the design.

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