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HIGH TEMPERATURE ELECTRONIC REQUIREMENTS IN AEROPROPULSION SYSTEMS

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Summary

This paper discusses the needs for high temperature electronic and electro-optic devices as they would be used on aircraft engines in either research and development applications, or operational applications. The conclusion reached is that the temperature at which the devices must be able to function is in the neighborhood of 500° to 600° C either for R&D or for operational applications. In R&D applications the devices must function in this temperature range when in the engine but only for a moderate period of time. On an operational engine, the reliability requirements dictate that the devices be able to be burned-in at temperatures significantly higher than those at which they will function on the engine. The major point made is that semiconductor technology must be pushed well beyond the level at which silicon will be able to function.

Introduction

The purpose of this paper is to describe the needs for high temperature electronics in the aircraft engine field. The viewpoint expressed is as seen from the Lewis Research Center of NASA in light of the fact that a major element of the Center's mission is to perform basic research and development aimed at improving aeropropulsion systems. This view is also based on discussions of the topic with many other groups involved in aeropropulsion both in government and industry.

The major areas of research and development in the aircraft engine field today are: (1) higher fuel efficiency, (2) greater durability, and (3) reduced emissions, both gaseous and acoustic. There is a fourth major area of work which is not tied so directly with laboratory research and development but with flying operational engines. This area is the reduction of direct operating cost via reductions in the cost of maintenance and improvements in control systems. This may well be the most significant motivator of all when one gets to the bottom line.

In this paper we will endeavor to show that all these areas of work, separately and together, provide strong motivation for development of high temperature electronic and electro-optic devices.

Requirements for Ground Testing of Engines

In this section we will discuss the need for high temperature electronics for operation on the hot rotating turbine disks of engines used for research and advanced development. One urgent requirement is for a multiplexer operating at 500° to 600° C.

The development of a new aircraft engine is a very long and expensive process. The process can take as long as 10 years from start on the drawing board to first engine certified to fly. During this process many prototypes are built for testing and development purposes. These prototypes, as well as individual engine components, are operated repeatedly in ground test facilities. For each of these test runs the engine or component is instrumented with the maximum number of sensors possible so that as much of the desired information as possible is obtained from each facility run. Even after an engine is certified for flight, problems arise in its operation on aircraft, or ways of improving its operational characteristics become apparent so that this testing process continues well into the useful life of an engine model. An example of this is the REFAN program conducted by NASA to modify engines like those on the DC9 and the Boeing 727 to reduce the acoustic noise. This model engine had been in service for many years but new pressures generated by environmental concerns made it desirable to go back and redesign parts of it for reduced noise emission. This program, by the way, led to the improved engine now on the new stretched DC9.

The net result of all this is that engine and engine components receive a lot of testing and this is a very expensive process. An individual new engine can cost a few million dollars per copy. It can take the order of twenty of these to come up with the first certifiable copy. The cost to tear down an engine, put in new sensors and wiring, and rebuild for another test run is frequently upward of a quarter million dollars. On top of all this is the fact that the cost of performing the test run itself is skyrocketing because of the rising cost of engine fuel and test facility operating power. A typical engine test stand capable of altitude flight simulation uses upwards of 50 megawatts.

These testing costs provide a tremendous impetus toward getting as many sensors on an engine at one time as possible in order to reduce the number of rebuilds and test runs. This is accentuated by the fact that every rebuild generates a possible assembly error which on rare occasion can result in catastrophic failure causing loss of engine and/or part of the facility itself.

What currently limits the number of sensors which can be installed and utilized for one test? To answer this one must look at the current reasons for engine R&D. As was mentioned in the Introduction, two of the main motives for R&D are reduced fuel consumption, and greater durability. In this area of work, detailed measurements on the hot rotating turbine are required. The example we will discuss is the need for data from this turbine. Here is where the need for high temperature electronics arises.

A fundamental law of thermodynamics, the Carnot theorem, says that greater efficiency results from higher turbine inlet temperature. Another fundamental law (related to that of Murphy) says that hotter rotating machinery is either less durable or weighs more. Part of the process, then, of producing more efficient and durable engines is one of obtaining information about the temperatures and stresses within the turbine to a level of detail never before attempted. The level of detail needed in a particular section of the engine is, in fact, proportional to the severity of conditions in that section because the margin for error is less in those sections where the temperatures and stresses are the greatest. This leads to the need for far more data than ever before from the turbine disks and blades. This is the hottest part of the engine other than the combustor itself. In the turbine the temperatures are not only very high but they are also very non-uniform due to cooling flow through small bleed holes within the blades.

These very same conditions that make full instrumentation of the turbine mandatory also make reliable instrumentation most difficult. In a turbine test of this type, it is necessary to obtain data from the order of one hundred sensors, like thermocouples and strain gages, mounted on the rotating blades and disks. All these sensors can be mounted but routing the leadwork becomes impossible. One is faced with routing a few hundred wires down from the blades and/or disk to the shaft. From here they must be routed through a hole in the hollow shaft out to some transmission device such as a slip ring assembly or telemetry device to get the data from the rotating shaft to the stationary data handling equipment. The problem is that the hole is too small and/or the wires are too thick. If the hole is made bigger, the shaft has too little strength and its mechanical resonant frequencies begin to lie in dangerous regions. If the wires are made too thin, they break either in installation and/or in operation. Compounding this problem, in full scale engine testing, is the fact that there is no telemetry system available today which is capable of handling all these channels of data simultaneously in the severe environment where it must be located.

The current practice is to bring all the wires to the disk but connect only as many as can be brought through the shaft. After testing is complete with this configuration, the engine is torn down solely to allow connecting another batch of the wires. This process is repeated maybe three to five times until all the data is obtained. Not only is this a terribly expensive process but by the time you get to the third or fourth reassembly of the engine, many of the sensors and/or wires have failed from either the rigors of testing or those of disassembly and assembly. This whole situation is obviously not very good.

What is needed is electronics which can function in the environment in the region of the turbine disk. Here the temperatures are in the neighborhood of 500° to 600° C and the centripetal accelerations are tens of thousands of G's. What is needed most urgently is a multiplexer so that all the sensors can be read out during a single test run. Given the technology to build the multiplexer, the next item of interest may be some form of analog to digital converter capable of handling the millivolt level signals from thermocouples. Additionally, a high temperature telemetry system to send the signals from the rotating shaft to a stationary receiver would be highly desirable. The ideal would be one that requires no cooling because getting cooling air flow to these regions is not only complex and expensive but also the cooling air flow itself upsets the conditions in the engine to some extent. It should be noted that the capability for telemetry, multiplexing, and analog to digital conversion in this environment, except for the high temperature, has already been demonstrated.

What we have described here is the need for rugged electronics to be used at sink temperatures of about 500° or 600° C. It is most important that these devices work reliably for the order of 50 to 100 hours at test conditions. This is not continuous operation, though, because typical test runs last from 2 to 10 hours. More will be said about reliability in the next section when we deal with the problems encountered on engines that are on operational aircraft.

Requirements for Operational Engines

In this section we will develop the needs for high temperature electronics on operational engines. Even though we will arrive at the same temperature level requirement of 500° to 600° C, it will be for a different reason. The functioning temperature level of the electronics on an operating engine will be about 300° C but reliability will dictate a much higher burn-in temperature.

The most significant problem with operational aircraft engines today is that their direct operating costs are too high and getting higher. Certainly the rising cost of fuel is a major contributor to this problem. It is the root reason for the R&D aimed at reduced fuel consumption. However, fuel costs are not the only major constituent of direct operating cost. Another major factor is engine maintenance. As the engines become more sophisticated and complex in the interest of reduced fuel consumption and lower weight, they also become more difficult and costly to maintain. This has led to emphasis on greater durability and to modularization of engine designs.

Because we seem to be hammering away at costs so hard here, the reader may get the impression that these problems apply primarily to the civilian fleet. Not so. The military is also acutely concerned with these cost problems both because of their budget constraints and because they are flying the latest, most sophisticated engines which have not yet developed the maturity and refinement of design that usually leads to reduced maintenance costs.

How does one know when to pull an engine from service and tear it down for maintenance? The most common criterion is that a particular component of the engine has operated for a predetermined number of hours or cycles. Another common criterion which is used to determine when to remove an engine is that the required thrust cannot be achieved without exhaust gas temperature exceeding a permissible level. This temperature is monitored for just this purpose. If this temperature gets too high the turbine life is drastically reduced. There are other criteria used for removing an engine such as the belching of strange looking flames or smoke from the tail pipe or the emission of atypically cacophonous sounds and vibrations. Though these will not be considered significant for the purposes of this paper, they are usually considered urgent in the extreme by those aboard the aircraft.

The approaches to maintenance described above are not necessarily cost effective. The fact that an engine has operated for a given number of hours or cycles says nothing of the conditions under which it operated. In the interest of safety, these intervals are usually set shorter than really necessary so that maintenance is frequently performed on an engine that really does not need it. Exhaust gas temperature is only a very gross indicator of health so that the engine may be in sore need of maintenance before this criterion demands it. An alternative approach, which has been tried with some instances of success, is an engine monitoring system. The ideal monitoring system would be on the engine. It should collect data on selected engine parameters and process this data to a form that indicates whether the engine needs maintenance, points to the component needing the maintenance, and, perhaps, specifies what maintenance is needed. Such a system, coupled with the modularity of modern engines, will allow rapid access to the parts needing repair or replacement based on actual performance data. However, the modularity requirement dictates that at least some of the electronics required for engine monitoring be located on the engine.[1]

The need for such an engine condition monitoring system leads rather directly to the need for high temperature electronics. The devices needed here are for sensor signal conditioning, signal transmission, and a monitoring computer. Compared with the requirement discussed in the previous section on ground testing needs, the device requirements dictated by this monitoring system at first appear to be quite benign. There are far fewer sensors needed. They are probably not in the rotating environment. The signal conditioning, transmission, and computing equipment will not be located right in the very hottest parts of the engine but on the outside casing somewhere where the temperatures are lower. Careful consideration of this system, though, leads to the conclusion that the requirements may well be as difficult to satisfy.

The operating temperature requirements for this monitoring system usually come out to be about 300° C for high performance military aircraft or the possible future supersonic transport.[2] This temperature is set by the fact that the coldest air available at maximum speed and altitude is at what is called ram air temperature or total temperature at these flight conditions. Every other available fluid temperature, except that of the fuel, is higher. Fuel cooling of the electronics is now being used in some cases but it is very undesirable from the standpoint of complexity, weight, and leak potential. Thus 300° to 400° C seems a reasonable target for flight engine monitoring devices. This level does not seem very severe until one considers the problem of reliability.

Whereas, in the previous section we came up with operating time requirements of about 100 hours, in the flight monitoring system we need thousands of hours of absolutely trouble free operation. The primary reason for this is that you will not reduce maintenance cost if your monitoring system fails. Failure of the monitoring system will result in either premature engine repair or in monitoring system repair or, far worse than these, the indication that the engine is healthy when it is not. This leads to the inescapable conclusion that very high reliability is needed.

Common practice for achieving high system reliability for a given functional temperature is to use components that have been burned-in at a significantly higher temperature in order to weed out potential failures. The higher the burn-in temperature, the shorter the burn-in must be to weed out the bad parts. An acceptable burn-in temperature would be about the same as the temperature required for ground test applications discussed earlier.

A further requirement on operational engines arises from the need for more sophisticated engine control systems. This is being pursued by going to all electronic controls. These controls are required in order to achieve peak performance with high efficiency, long life, and safety. Requirements for modularity, flight safety, and combat survivability dictate that this control system be located on the engine.[2] This puts it also in an environment like that discussed for the monitoring system. Indeed the control computer may also be the monitoring computer. Thus, engine control requirements result in about the same environmental and reliability needs for electronic devices as do those of the monitoring system.

We should point out here that there is also a need for optic and electro-optic devices to operate on the engine. This need arises primarily in military aircraft. Fiber-optic, rather than electronic cable, transmission of data from place to place on the aircraft brings the significant advantages of enhanced freedom from electromagnetic interference and the ability to send data over multiple paths without incurring the weight penalties of multiple electronic cables. Since much of the data originates on the engine, at least some of the electro-optic devices and fiber optic bundles will reside on the engine and therefore have to operate reliably in the same thermal environment as the monitoring and control electronics.

To summarize this section, the needs of operational aircraft engine monitoring and control dictate electronic and electro-optic devices capable of very high reliability while operating at temperatures not too much higher than 300° C. This reliability requirement, we believe, will require burn-in at the 500° to 600° C temperature level.

Concluding Remarks

In this paper we have discussed the needs for high temperature electronics and electro-optics as they would be used on aircraft engines in research, development, and operation. The conclusion reached is that the temperature at which the devices must be able to function is about the same either for R&D or for operational applications though the reasons for arriving at this estimated temperature are quite different. In R&D applications the devices must function at this temperature when in the engine but only for a moderate period of time. On an operational engine, the reliability requirements dictate that the devices be able to be burned-in at temperatures significantly higher than those at which they will function on the engine.

We have been purposely vague in defining the temperature goal as being around 500° to 600° C because there are arguments for a goal a hundred degrees above and below this temperature range. The major point to be made is that we must push well beyond the level at which silicon will be able to function.

As a final thought, we would like to say that all of this constitutes the justification needed to get support for a program aimed at high temperature electronics. It probably has little to do with the most significant future applications of these devices. They are presently unknown. Consider the original justifications for developing integrated circuits. They were to enable small, low power circuitry for spacecraft applications. As it has turned out, they were indeed useful for these purposes but these uses have proven to be of trivial impact on society relative to the other, more mundane uses to which they are now being applied. At Lewis we had a high temperature electronics program going in the late 60's and early 70's aimed at the needs of nuclear power systems for spacecraft. When that was no longer supported the electronics program went down the tubes with it. Now we are starting up essentially the same program for completely different reasons. We cannot help but feel that high temperature electronics will indeed have wide application not only to the areas discussed at this conference but also to far more important areas which we just do not have the vision to predict.

References

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