SHUTTLE SENSORS

VERNON C. MELLIFF, JR.

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

AND

ARTHUR T. LINTON

THE BOEING COMPANY
HOUSTON, TEXAS

SUMMARY

The typical Shuttle environments that constrain the performance of the required Shuttle sensors are described. The maximum environmental temperatures for sensors are expected to be -300°F to +650°F (-184°C to +344°C) for large portions of the wing area and fuselage. The new high temperature materials present many unique sensor design problems with regard to sensor installation and calibration. Operational requirements of the Shuttle sensors are much more stringent than of previous spacecraft — life expectancy is 10 years, 100 missions between major repair work, and rapid turn-around time between missions (2 weeks limit).

With consideration of the Shuttle requirements, this paper discusses pressure, temperature, strain, acceleration, vibration, and acoustic transducers; their inherent design deficiencies; and suggested methods and approaches for solution of these deficiencies.

INTRODUCTION

This paper will address some of the more significant constraints on sensor technology relative to the Space Shuttle Program. No attempt will be made to cover all of the constraints on the Shuttle sensors, nor will the paper discuss all the required types and their applications.

The sensors referred to in this paper are the types which are required to verify the vehicle performance during the flight test phase and also to provide information for the operational control of the vehicle. These sensors will be required to perform for many missions over a relatively long period of time and under very severe environmental conditions.

This paper is a summary of the preliminary requirements for Shuttle sensors; and the quantity, location, and temperature environment limitations are indicated.

Next, we will discuss the significant constraints that will influence the need for sensor development, such as high temperature, advanced materials, and program requirements. Following that, I will discuss five or six sensors most commonly used, their limitations, and some possible solutions. Finally, we will present some overall conclusions.

OUTLINE

- SUMMARY REQUIREMENTS
- SIGNIFICANT CONSTRAINTS
  - HIGH TEMPERATURE SHUTTLE ENVIRONMENT
  - SHUTTLE MATERIALS
  - PROGRAM REQUIREMENTS
- SPECIFIC SENSOR CONSIDERATIONS
- CONCLUSIONS

SHUTTLE SENSOR REQUIREMENTS

The following chart is shown to give you an understanding of the magnitude of the problem. We have shown three general vehicle locations with the expected quantity of transducers in each location. You will note that the majority of the sensors will be in the moderate to severe environments, such as the wing, fuselage areas, and the surface.

The Shuttle may use off-the-shelf sensors for approximately one-half these requirements, providing they are judiciously selected and evaluated with respect to their installation. Furthermore, technology does exist to support the other sensor requirements, but the application of the technology to the specific sensor hardware will require development.

The sensor cost is a concern. An average sensor may cost $1,000; however, with the addition of wiring, signal conditioning, installation effort, calibration, test, checkout, maintenance, and documentation, the cost may well run to 10 times this amount. The total cost for Apollo measurements was over $100 million, and with the Shuttle preliminary requirements projected four times larger than on Apollo, costs could be significant.

PRELIMINARY SHUTTLE SENSOR REQUIREMENTS

SENSOR TYPE	CABIN 0° TO 200° F	WING/FUSELAGE -300° TO 650° F	SURFACE -300° TO 3000° F
PRESSURE	28	567	
TEMPERATURE	98	2078	856
STRAIN		60	146
VIBRATION & ACCELERATION	2	178	40
ACOUSTICS	2	120	
FORCE	4	8	
DEFLECTION		6	
SPEED (RPM)	12	10	
RADIATION	2		
HUMIDITY	3		
PARTIAL PRESS	5		
QUANTITY	6	10	
FLOW	8	8	
PH	4		
TOTALS	174	3045	1042

SENSOR CONSTRAINTS

- **HIGH TEMPERATURE SHUTTLE ENVIRONMENT**
- **SHUTTLE MATERIALS**
- **PROGRAM REQUIREMENTS**

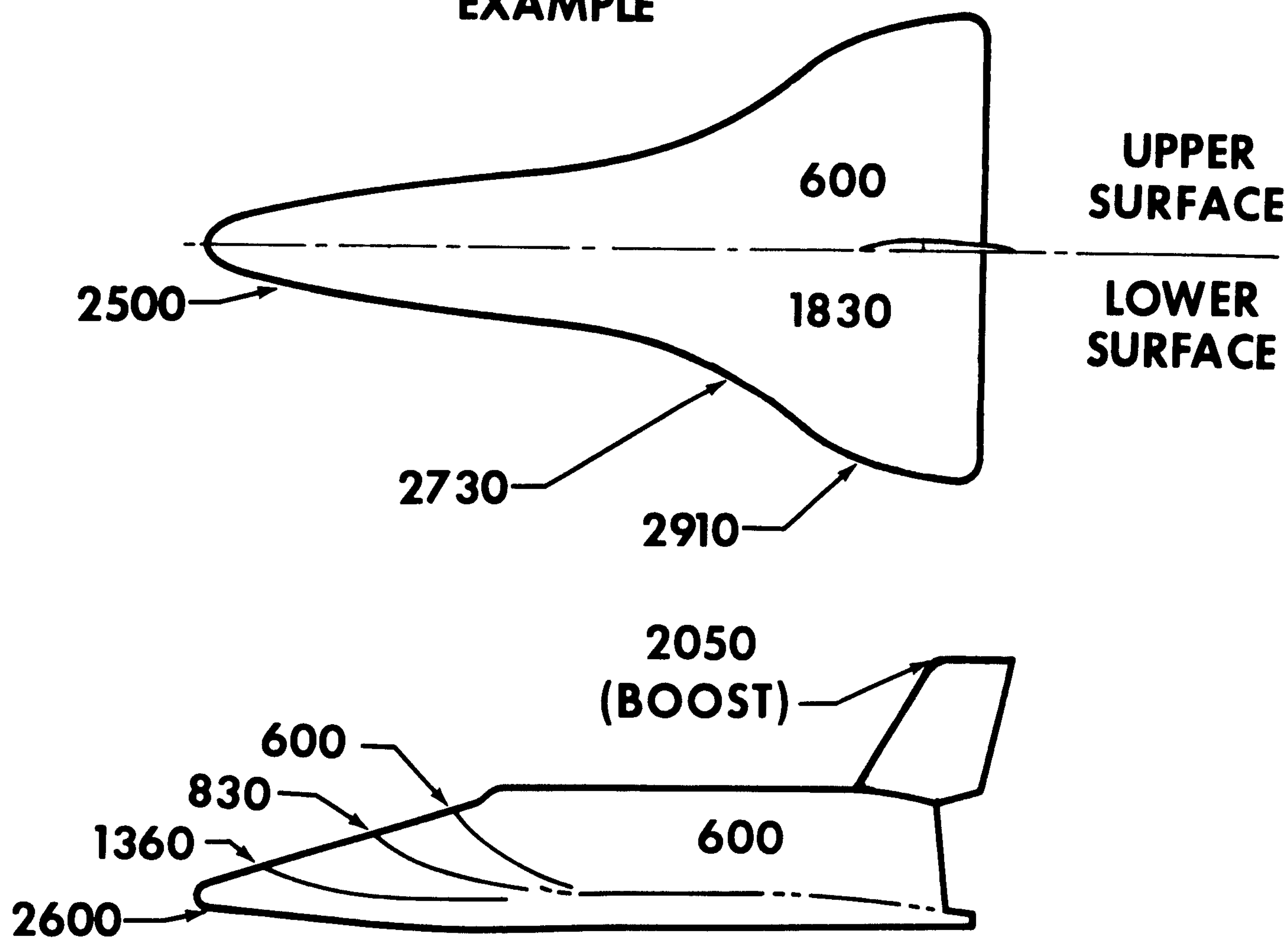
MAXIMUM SURFACE TEMPERATURES

The maximum expected surface temperatures shown are proposed by one of the contractors for the Shuttle's study phase. Although the temperatures may deviate from this, it does provide an example of probable conditions.

You will note the upper surface will be near 600°F (316°C) and the bottom surface near 1830°F (999°C) for the entry phase of the mission. The nose stagnation temperature reaches 2600°F (1404°C) and the leading edge a maximum of 2910°F (1599°C). During the boost phase, the vertical fin tip reaches a peak of 2050°F (1121°C).

MAX SURFACE TEMPERATURES °F

EXAMPLE



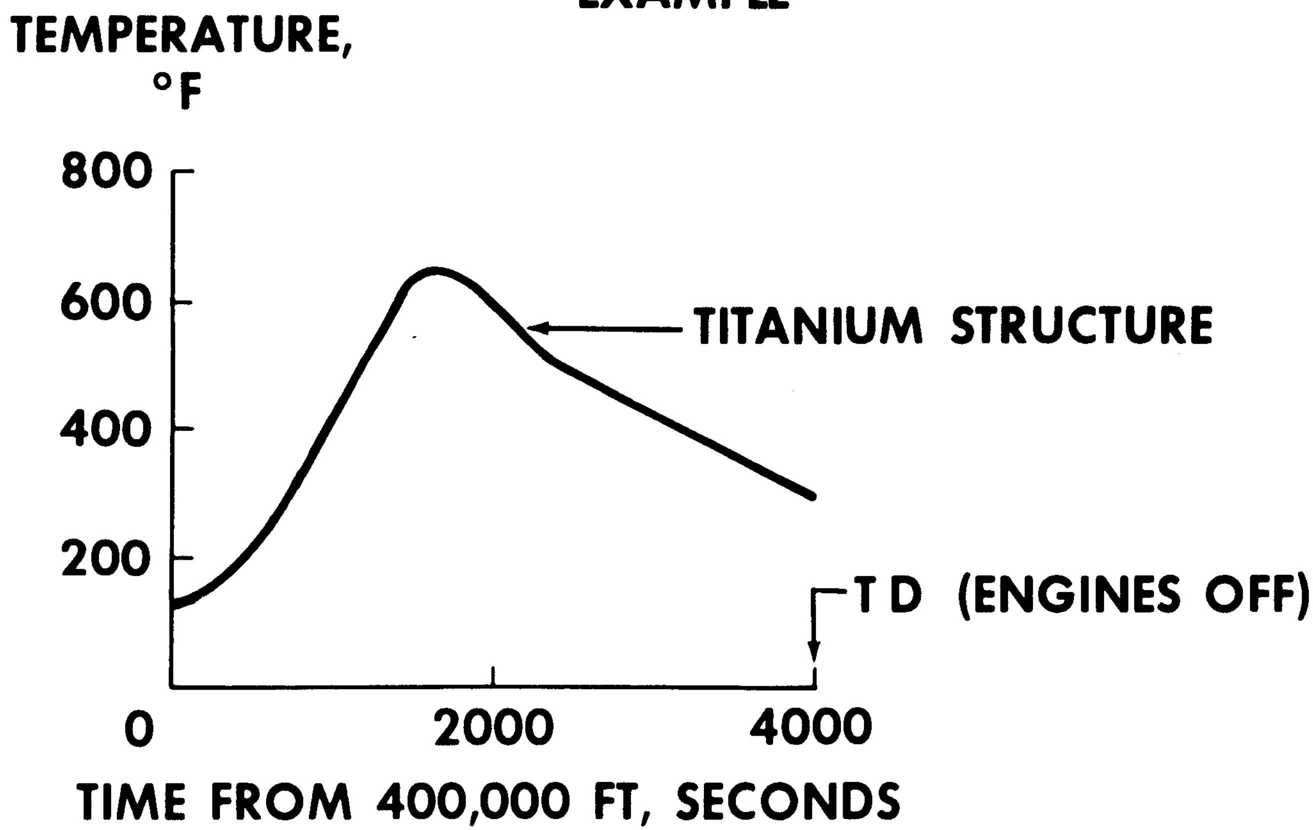
SUBSTRUCTURE TEMPERATURE RESPONSE

The following slide represents the internal responses due to the upper surface thermal environment during entry. The response from the lower surface is almost identical, or should be if the thermal design is correct, even though the temperatures are much more severe.

The prime data are required during the first 15 to 20 minutes of entry, which is in the area of the the most rapid environmental change, and thus have the greatest impact on the transducer accuracy. Pressure measurements, for example, will be affected because of unequal thermal conductivity within the sensor producing mechanical distortion.

SUBSTRUCTURE ENTRY TEMPERATURE RESPONSE

EXAMPLE

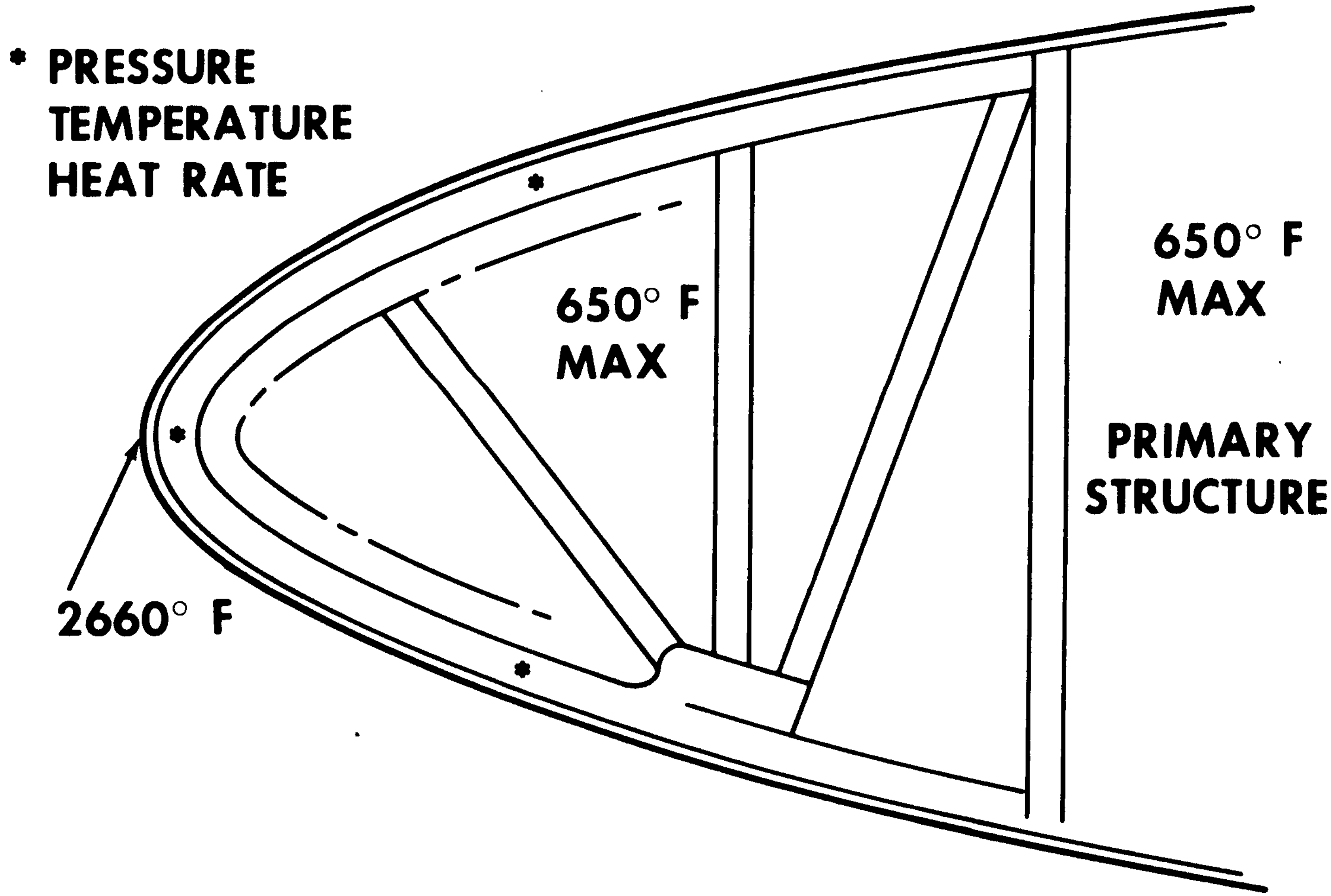


WING LEADING EDGE

Indicated by the following slide are typical sensor locations as may be required by aerothermal engineering. The internal structure design is presently being based upon a maximum of 650°F (343°C), not only at the leading edge, but throughout the entire wing area.

The major problems are, again, the method, process, and procedures to install sensors such as pressure transducers, thermocouples, and calorimeters into these new high temperature materials. The integrity of the instrumentation must be verified in that it will not weaken or destroy the basic structure. Also, the effect of the instrumentation mass and weight must be determined with respect to the materials, such as titanium or columbium. Another concern is that signal conditioning cannot be integrally installed with transducers in the wing unless a means is developed to operate solid-state devices at these temperatures. This is a big change from the Apollo transducers, which primarily had signal conditioning with or adjacent to the transducer.

WING LEADING EDGE

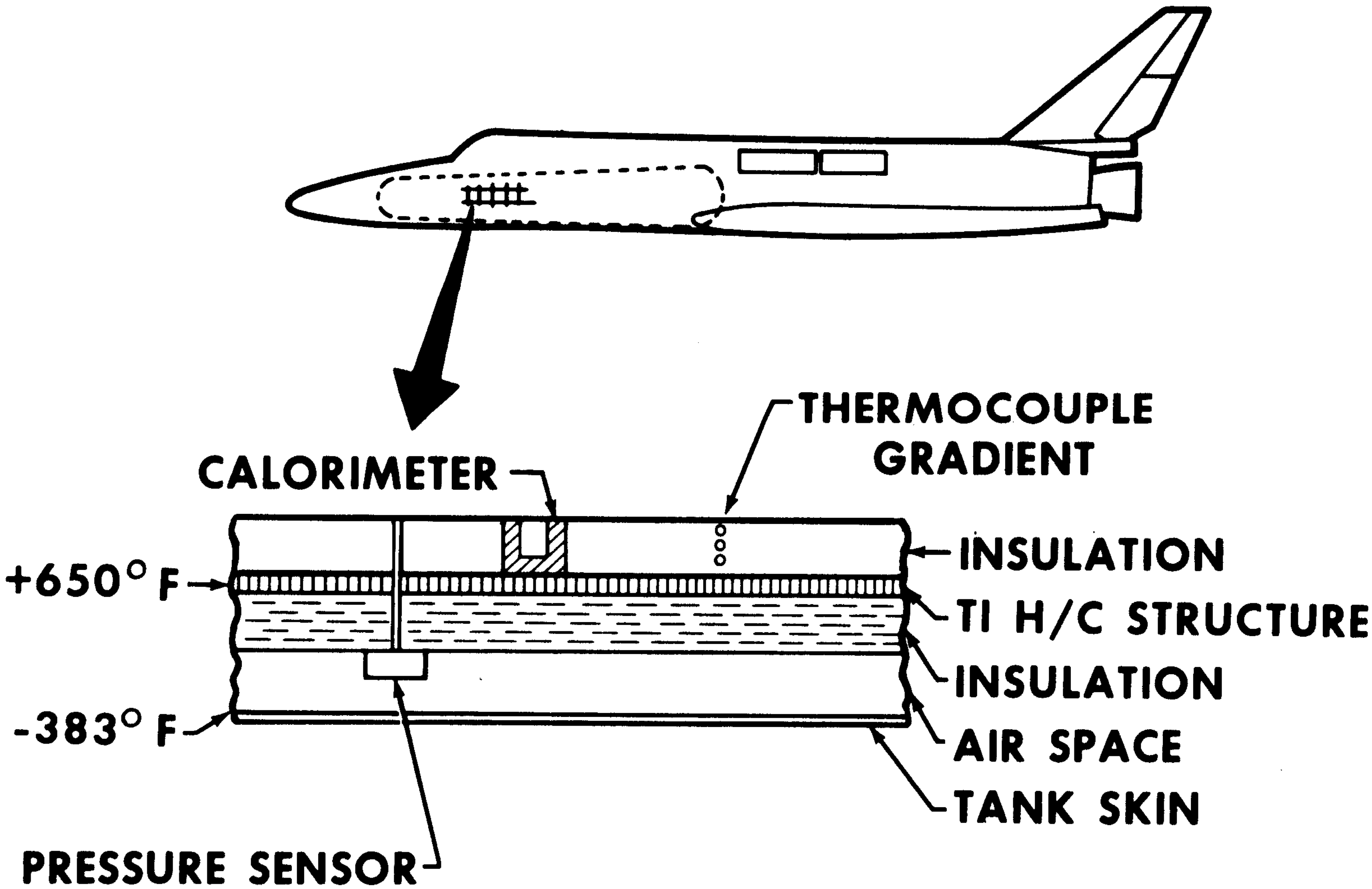


FUSELAGE TANK AREA

The following slide shows some examples of sensor locations in the fuel tank area which are in a most severe environment. These temperatures represent the best available information with the configuration presently defined.

During the boost or launch phase, the tank surface is expected to be -300°F (-184°C) before launch, with the titanium honeycomb structure going to +150°F (66°C) in 200 seconds after launch. Before entry, the tank skin could be as low as -383°F (-231°C), with the titanium structure going to 650°F (343°C) about 1500 seconds after the initiation of the entry phase.

FUSELAGE TANK AREA

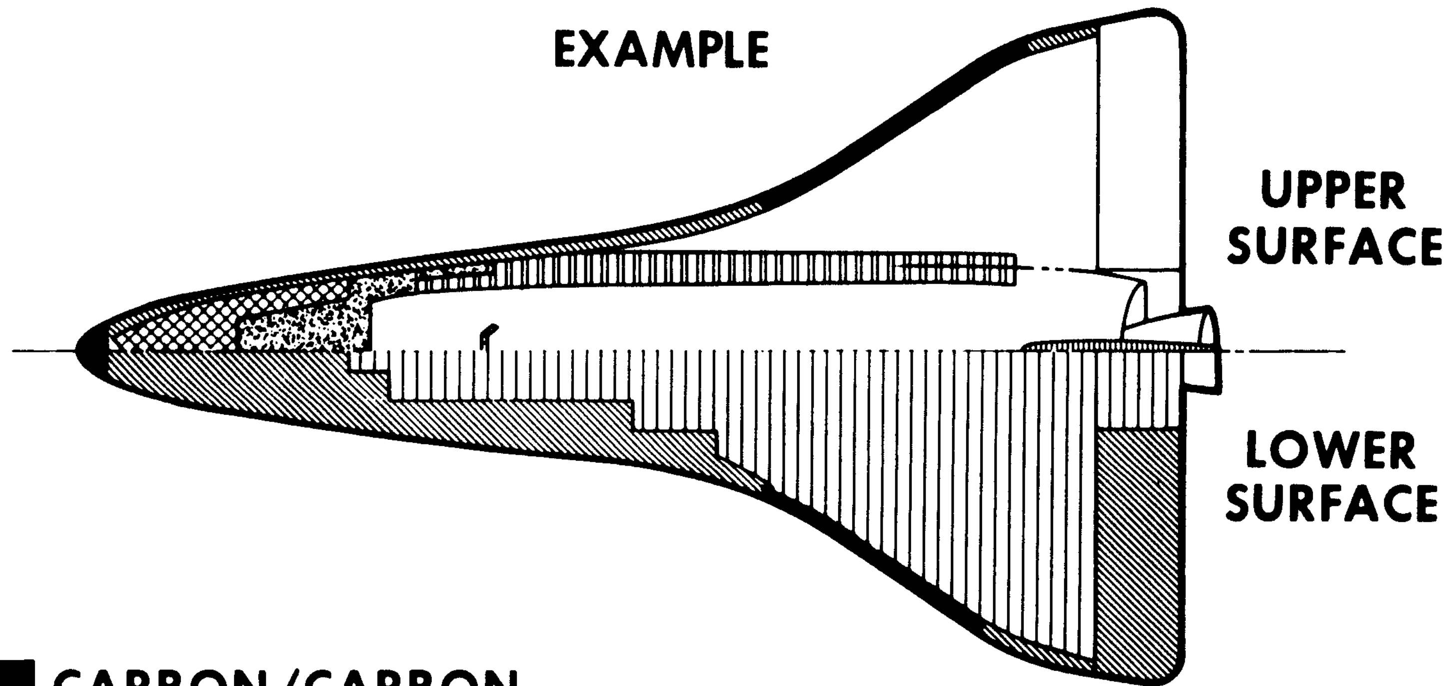


PROPOSED SURFACE MATERIAL DISTRIBUTION

The instrumentation designer on the Shuttle is faced with a large variety of exotic materials. Problems of how to install thermocouples, strain gauges, and calorimeters in, on, and through these materials present challenging installation designs. Many of these metals are coated with materials that cause additional problems, such as the columbium metal which has a chromic oxide coating. Each of these new materials will undoubtedly require a careful design and verification test program to insure proper instrumentation performance. These surface materials imply another problem for the instrumentation people in that each material may require sensors matched to the material characteristics, which will further multiply the sensor types. This is not a happy thought when we are trying hard to promote commonality and cost effective design.

SURFACE MATERIAL DISTRIBUTION

EXAMPLE



CARBON/CARBON
COLUMBIUM (FS-85) SHINGLES
HASTELLOY X SHINGLES
RENE' 41-SHINGLES
INCONEL 718-SHINGLES
RENE' 41-HOT STRUCTURE
TI (6AL-4V)-HOT STRUCTURE
TI (6AL-4V)-SHINGLES

PROGRAM REQUIREMENTS

The program requirements establishing a 10-year operational life for a vehicle is extremely difficult for the Shuttle sensors. With multiple flights over an extended period of time, many failures of sensors will occur unless adequate preventive measures are taken. Although sensors have been used on experimental aircraft during their test programs, in most cases the operational life of these units has been relatively short (under 5 years) and not required to meet the unique environments anticipated for the Shuttle. The present flight test plans establish a 2-year period for the horizontal test phase (in atmosphere) and a 2-year period for the vertical test phase (orbital). Since most of the sensors are for the test phase, the flight test plans dictate a 2-year life for these sensors. Also, the 100-mission requirement implies about a 2-year period between major maintenance work on the Shuttle. Therefore, accessible sensors could be replaced during these periods if it were mandatory for the mission. Some sensors will be inaccessible and will require special attention for design life, stability, and calibration. Strain gages have a definite operational life limit and require consideration in flight test planning. For example, based upon X-15 flight test experience, it is estimated that over 20 percent of the Shuttle strain gages (5000 micro-strain type) will fail before 2 years of operation; therefore, a concept of excess measurements for strain must be considered.

Downtimes during a flight test program are costly and unproductive because essentially the program is waiting for the data to verify the design. Range changes to measurements are the most common, usually because the initial selection is an approximation. The designers should accept this challenge to develop transducers with multiple ranges, selectable at the transducer or preferably at the signal conditioner, with no increase in cost. Of course, this would add to the complexity of the system, but on some critical Shuttle measurements, it may not only be desired but mandatory. Also, there will be areas of critical measurements that will be inaccessible. In these areas, it would be desirable to install redundant transducers to insure results in the event of a transducer failure.

The 2-week turn-around time between landing and launch will stress simplicity and efficiency in performing calibration, minor modification, and repair of sensors. There appears to be no clean-cut and cost effective method of performing the Shuttle sensor calibration. There will probably be many different calibration procedures based on the type of sensor, location, criticality, and design stability.

Accuracy requirements should be very carefully reviewed because unnecessarily severe requirements could be a significant cost driver. Most measurements are required during a relatively short span of the mission. The accuracy tolerance should be specified for that period and verified to that environment.

PROGRAM REQUIREMENTS

- LIFE - 10 YEARS
- 100 MISSIONS - MINIMAL REPAIR
- RAPID TURN-AROUND BETWEEN MISSIONS

PRESSURE TRANSDUCERS

Most of the pressure measurement requirements for Apollo have been met by utilization of the strain gage diaphragm type pressure transducer with integral or separate signal conditioner and power supply. Other test programs have utilized variable reluctance, linear variable differential transformers, and piezoelectric principles in the basic transducer.

Strain gage types, specifically vacuum-deposited thin-film strain gage transducers, and deposited semiconductor gages appear to offer the most potential. The major problems are caused by temperature changes resulting in uncompensated diaphragm deflections and changes in lead wire resistance. There are methods for reducing the effect of resistance changes. These include utilization of constant current excitation sources and the installation of additional wiring to record the actual voltage at the transducer. These methods will provide very accurate data over the temperature range expected in the Shuttle interior; however, when temperatures are rapidly changing, as during boost and entry, unacceptable errors may result. Recent developments in quartz diaphragms indicate that little development may be required to provide transducers for higher temperature environments with more rapidly changing temperatures than presently available.

Also, consideration should be given to using transducer thermal control to minimize measurement errors due to rapidly changing temperatures. Approaches that might be considered are:

a. Providing individually controlled heating to maintain temperatures at maximum operating temperatures.

b. Design of individual or small group evaporative type coolers operating on the water boiler principle. This would consume a considerable quantity of water and be subject to human error.

c. Cooling by means of latent heat of fusion. This method requires use of a material having a suitable low melting point so that it absorbs heat without appreciable temperature increase until all of the material melts.

Very low range pressure transducers will experience diaphragm damage when exposed to the ambient pressure. A limited diaphragm displacement transducer is, therefore, required.

The presently available pressure transducers will operate satisfactorily up to a temperature of about 650°F (344°C). But where it is necessary to monitor pressure at the skin surfaces, a source tube must be used to separate the transducer from the severe thermal environment. Shock tube calibration will then be required to determine the measurements transient response. The transient response of a diaphragm transducer depends upon the cavity volume of the transducer and the diameter and length of tubing which connects the transducer to the pickup point in the system being measured. This latter factor is an additional source of error. The sensor manufacturer will have to work closely with the vehicle design engineers to develop an optimum mechanical configuration to achieve the response required in particular applications.

PRESSURE

- RANGE
  - 0 TO 1600 PSIA
- IMPACT
  - MOST REQUIREMENTS SATISFIED WITH OFF-THE-SHELF SENSORS
  - PRESENT CAPABILITY 650° F (STATIC)
- PROBLEM AREAS
  - RAPID TEMPERATURE CHANGE
  - OVERSTRESS OF DIAPHRAGM AT LOW RANGE
- POSSIBLE SOLUTIONS
  - INTERNAL HEATERS
  - LIMIT DIAPHRAGM DISPLACEMENT

TEMPERATURE

The skin temperature sensors will be subjected to the most severe thermal environment on the vehicle. Therefore, this section will concern itself primarily with the design of sensors to meet this severe environment. Design selection will favor thermocouples since development problems of thermocouples are considered to be more amenable to solution than for resistance element surface sensors, because the resistance element sensor utilization would require the solution of the problems of bonding to exotic materials and thermal insulation resistance degradation.

Skin surface temperatures on the Shuttle orbiter are expected to reach temperatures in the order of 3000°F (1480°C) during boost and/or entry. Similar thermal conditions were anticipated on the X-20A (Dyna-Soar) vehicle. Temperature measurements were performed on the Apollo Command Module heat shield using thermocouples at temperatures in excess of 3000°F (1480°C).

The Dyna-Soar initial thermocouple design consisted of a tungsten/tungsten-26% rhenium (W/W-26 Re) thermocouple insulated with compacted magnesium oxide and clad with 0.065-inch OD tantalum. The junction was formed by swaging a molybdenum plug into the end of the sheath between the thermocouple wires. The installation was performed by first swaging a molybdenum rivet into a dimpled hole in the skin. The rivet was then drilled, the transducer inserted, and the rivet crimped to hold the thermocouple in place. For oxidation protection, the rivet and the transducer were individually disilicide coated before installation and then the complete assembly was coated after installation.

It was found that the pure tungsten leg of W/W-26 Re became brittle after heating. Tests made with samples of W-5 Re/W-26 Re showed poor ductility repeatability from batch to batch, in addition to discontinuities in the wires. As a result of these evaluations, Pt/Pt-13 Rh was selected as the prime material. The Pt/Pt-13 Rh combination was chosen because it has a higher thermoelectric output than Pt/Pt-10 Rh, although it is slightly under the minimum specified output of 20 millivolts at 3000°F (2968°C).

The Apollo Program employed W/W-26 Re thermocouples also. No problems were encountered because of the relatively short temperature cycle time.

From the foregoing discussion, it is evident that extensive development effort has been expended on high temperature thermocouples. No difficulty should be encountered in the selection of a thermocouple to be compatible with the expected Shuttle environment. A temperature measurement system accuracy of 5 percent may be attained by thermocouple calibration prior to installation. The measurement channel characteristics are then adjusted to match that of the thermocouple calibration. One area which may require development is the installation techniques of thermocouples on the Shuttle skin. However, because of industry experience in thermocouple installation, this is not believed to be unsolvable.

TEMPERATURE

- RANGE
  - -440°TO +2700° F
- IMPACT
  - MEASUREMENTS ON HEAT SHIELD SURFACES
- PROBLEM AREAS
  - MOUNTING IN MATERIAL
  - INTEGRITY OF STRUCTURE
  - SENSOR DISTURBANCE ON NATURAL ENVIRONMENT
- POSSIBLE SOLUTION
  - DESIGN AND FABRICATE AS AN INTEGRAL PART OF HEAT SHIELD ASSEMBLIES

STRAIN

The measurement of structural strain is complicated by the high temperature environment and the limited industrial experience in the installation of strain gages on exotic materials.

Conventional high temperature strain gages are limited to approximately 600°F (316°C) for static strain measurements, and 1500°F (816°C) for dynamic measurements. For dynamic measurements, a higher temperature may be tolerated because the temperature induced drift is of low frequency compared to the data and may then be filtered out. The upper temperature limit is primarily determined by the loss of insulation resistance of the leads to each other and to ground. For example, the insulation resistance of a high temperature, weldable sheathed gage (Microdot SG 425) has a resistance to ground of 50 megohms at 1210°F (655°C) but drops to 8000 ohms at 1470°F (795°C).

During development of the X-20, several gages were investigated for operation at 1600°F (872°C). They included a weldable gage, free filament ceramic bonded gage, fiber glass backed gage, and a sprayed-on gage. None were able to withstand the temperature environment.

Present state-of-the-art gages can be used up to 1500°F (816°C). However, for higher temperatures, development work is required. Also, investigation is required in gage bonding on exotic materials. Gage bonding to exotic materials is probably the single most significant problem which must be solved before strain gages can be used on the Shuttle.

An alternate approach to measuring strain in the high temperature areas is the use of displacement transducers between two fixed reference points. The problem of gage bonding is thereby eliminated. The displacement transducer may be mounted a finite distance from the skin, which places the transducer in a less severe thermal environment. Typical candidate transducers are potentiometric, capacitive, or variable inductance. Further trade studies are necessary to determine which of these alternates provides the most cost-effective, accurate, and reliable approach to Shuttle structural strain measurement.

The problem of gage life is another factor for consideration. It has been industry's experience to expect large numbers of strain gage failures during a flight test program. However, failure mode examinations reveal the failures to be usually due to bond or lead failure for low range strain gages — rarely gage fatigue. For high range gages, fatigue failure is quite common. This again points to development required in the art of gage installation or the use of displacement transducers to measure strain.

STRAIN

- RANGE
  - ±5000 AND ±100,000 MICRO-STRAIN
- IMPACT
  - ±5000 MICRO-STRAIN CAPABILITY
    600° F STATIC
    1500° F DYNAMIC
  - ±100,000 MICRO-STRAIN CAPABILITY 150° F
- PROBLEM AREAS
  - GAGE BONDING TO EXOTIC MATERIALS AT HIGH TEMPERATURE
  - BASIC MATERIAL ELASTIC LIMIT
- POSSIBLE SOLUTION
  - EXPAND TEMPERATURE CAPABILITY OF DISPLACEMENT SENSOR

LINEAR ACCELEROMETERS

A large number of low frequency accelerometers will be required to conduct the flutter analysis program in the several flight regimes. For measurements inside the environmentally controlled areas, the presently used servo-type accelerometers will provide the required accuracy of ±2 percent full scale from 0 to 50 Hz. Some development effort will be required to achieve 2 percent accuracy below 2 Hz. These transducers at cabin temperatures are capable of excellent static and low frequency accuracy, and the main source of uncertainty will be in calibration.

For measurements outside the environmentally controlled areas, the situation is different because of the temperature environment and, again, calibration limitations which in this case will have to cover frequencies up to 20 Hz or higher for flutter tests. The presently used servo-type transducers will not survive the expected temperature environment in their current configuration.

For low frequency measurements, the servo-type accelerometer offers a possible solution, using some form of temperature conditioning. Several approaches were suggested in relation to the pressure transducer problem. Here again, development effort will be required to meet performance requirements.

LINEAR ACCELEROMETERS

- RANGE
  - ± 20 g (0 - 20 Hz)
- IMPACT
  - PRESENT CAPABILITY 325° F
- PROBLEM AREAS
  - ELECTRONIC THERMAL LIMITS
  - MATERIAL THERMAL CHARACTERISTICS
- POSSIBLE SOLUTIONS
  - THERMAL CONTROL

VIBRATION

For high frequency vibration measurements, the piezoelectric transducer appears to be the most promising. In the past, the maximum temperatures for piezoelectric transducers have primarily been limited by ferroelectric Curie temperatures and crystal phase changes. Quartz, which is often used, is limited to about 500°F (260°C). High piezoelectric strain constants are extremely important to provide adequate transducer output and small size. Accelerometers must be small and light to minimize their affect on structure motion. High bulk resistivity is also critical since the resistance of insulating materials decreases exponentially with temperature increase. A general rule is that resistance drops by a factor of 10 for each 212°F (100°C) increase. Thus, with a temperature increase from 70°F (20°C) to 1330°F (720°C), the resistance would drop by a factor of 10 million.

Present day calibration methods limit vibration sensor calibration to approximately 10 KHz. Experimental methods exist for calibrating in excess of 10 KHz, but refinements will be required to adapt these methods for use in industry.

Recently developed materials show promise of meeting the requirements for Shuttle vibration transducers. For example, PIEZITE P-15 piezoelectric material has a Curie temperature above 1750°F (954°C). Charge sensitivity varies little from room temperature to at least 1500°F (816°C), and the output is equivalent to those materials now used in accelerometers at lower temperatures. It is anticipated that further developments with this and other types of materials will permit development of suitable accelerometers for specific Shuttle requirements.

VIBRATION

- RANGE
  - 20 Hz TO 16 KHz
- IMPACT
  - PRESENT CAPABILITY TO 650° F
  - MEASUREMENTS NEAR HEAT SHIELD SURFACES 1500° F
- PROBLEMS
  - HIGH TEMPERATURE EFFECTS ON PIEZOELECTRIC MATERIALS
  - INSULATION RESISTANCE DECREASE
  - HIGH FREQUENCY CALIBRATION
- POSSIBLE SOLUTION
  - HIGH TEMPERATURE PIEZOELECTRIC MATERIAL BEING DEVELOPED

ACOUSTICS

Acoustic sensors are available which will adequately measure the sound level in the cabin. A capacitance type sensor may be used over the frequency range of 50 to 10,000 Hz with a required dynamic amplitude range of 40 dB.

However, acoustic measurements are also required in areas outside the cabin for structural fatigue studies. This imposes very severe temperature and differential pressure requirements on the sensor. Current technology dictates the use of a piezoelectric transducer with active cooling to satisfy the severe environmental condition, but the cost and weight penalty would be great. It is evident that considerable effort will be required to develop a sensor which will be compatible with the Shuttle environment. Recently developed high temperature piezoelectric material may be candidate for use in advanced high temperature acoustic sensors.

The calibration of an acoustic system is a complex procedure. The system must be calibrated prior to vehicle installation over the required frequency range at multiple sound pressure levels. Calibration must also be performed at representative operating temperature and pressure. A pressure-sensing feedback loop may be required to be incorporated in the sensor to provide pressure compensation.

ACOUSTICS

- RANGE
  - UP TO 140 dB CABIN
  - 140 - 170 dB STRUCTURE
- IMPACT
  - CAPACITIVE TYPE SUITABLE FOR CABIN
  - PIEZOELECTRIC TYPE FOR STRUCTURES
- PROBLEM AREAS
  - VARYING AMBIENT PRESSURE
- POSSIBLE SOLUTION
  - PRESSURE SENSING FEEDBACK

CONCLUSIONS

This paper has attempted to highlight the state of present technology in providing selected sensors capable of operating in the Shuttle environment. Some of the measurements may be implemented by using presently available sensors. However, the Space Shuttle presents certain temperature and materials problems which require continued developmental effort.

On the skin and adjacent internal areas, high temperature levels and high temperature rates of change are predicted. Sensors in these areas must withstand an environment exceeding the experience of any previously flown vehicle. Within this environment, the sensors must provide accurate data, be reliable, and be cost effective.

Thermocouples exist which will operate satisfactorily in the high temperature environment, but development effort is required to adapt strain gages, acceleration and vibration sensors, pressure transducers, and acoustic sensors to the Shuttle environment. The trend of development indicates that these problems are solvable. High Curie point piezoelectric material is being developed for use in accelerometers and acoustic sensors. Quartz diaphragm pressure sensors are being developed for extreme temperature applications. Many possible methods of measuring strain are under study. Near-term development will yield an acceptable system.

The second major problem is posed by the exotic materials to be used in construction of the vehicle. There is minimal industry experience in bonding instrumentation to proposed Shuttle materials. This is a very challenging problem, but cooperation between materials engineers and instrumentation engineers of NASA and industry will result in a satisfactory solution.

CONCLUSIONS

- SENSOR HARDWARE WILL REQUIRE DEVELOPMENT
- INSTALLATION TECHNIQUES MUST BE DETERMINED