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# **ADVANCED SENSORS AND INSTRUMENTATION**



**SPACE TRANSPORTATION AVIONICS  
TECHNOLOGY SYMPOSIUM**

**Williamsburg, VA  
November 7-9, 1989**

**ADVANCED SENSORS AND INSTRUMENTATION**

**WHITE PAPER**

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#### Background

NASA is currently investigating the readiness of Advanced Sensors and Instrumentation to meet the requirements of our nation's new initiatives in space. Pre-symposium, Space Transportation Avionic Technology (STATS), ad-hoc discussions were focused on identifying strategic sensor and instrumentation technologies. The content of this paper resulted from discussions between members of the technical staffs at Langley, Johnson, Marshall, and Rockwell International. Summary suggestions per organization are attached as appendixes to this white paper.

The STAT presentation was focused around the 8 quad charts, see Figures 1 and 2.

Not knowing the specific technical objectives of individual missions, the group identified and discussed the following strategic technologies:

- Smart and nonintrusive sensors
- On-board signal and data processing
- High capacity and rate adaptive data acquisition systems
- On-board computing
- High capacity and rate on-board storage
- Efficient on-board data distribution
- High capacity telemetry
- Ground and flight test support instrumentation
- Power distribution
- Workstations, video/lighting

The goal of this white paper is to capture the substance of the presentation and technology discussions during the subpanel meeting. The requirements for higher fidelity data (accuracy, frequency, quantity, spatial resolution) in hostile environments will continue to push the technology developers and users to extend the performance of their products and to develop new generations. In some technology areas, this process may acquire a strong active leadership from NASA. Thus, there is a need for a workshop just for Advanced Sensors and Instrumentation.

## Smart and Nonintrusive Sensors

Forecasts for the future include third and fourth generation sensor technology. Sensors with digital outputs, at sensor location, in engineering formats for distribution. Sensors with advanced dedicated signal processing such as fast fourier transform and digital filters at the sensing location. In many applications the sensors will have to be embedded in the surface or structure.

The nondestructive Measurement Science Branch, at Langley Research Center, is currently investigating innovative techniques in making nonintrusive measurements, for example, see Figures 3 through 6. Other nonintrusive techniques highlighted at the symposium included laser-based air data, Rendezvous/proximity, large space structures, and planetary surveys systems, see Figures 7 and 8.

Langley Research Center has initiated development studies for a laser-based air data system to replace the currently used pilot/static pressure, angle-of-attack, and angle-of-sideslip vane measurement system. Application of this system could extend to space transportation vehicles, and compliment the Shuttle Entry Air Data System (SEADS). Additional research funds are needed to make required advances in optics, lasers, and detectors to bring laser air data to fruition. Other key sensor areas discussed include: vehicle health performance monitoring, global position sensing, and guidance navigation and control.

## Signal and Data Processing Instrumentation

As with other instrumentation, signal conditioning must be optimum in utilization of weight, volume, and power. Advances in micro-miniaturization; and hybrid electronics are enabling intelligent processing at the measurement location. Thus, allowing on-site bandwidth reduction and digital outputs. Continued improvements along these lines provide efficient bandwidth utilization and weight reduction using state-of-the-art data buss technology.

## High Capacity and Rate Adaptive Data Acquisition

Current sensing instrument requirements (Eos) are exceeding the TDRSS data rates, see Figure 9. Therefore, the trend will be to develop on-board bandwidth reduction techniques, high capacity and high rate data buffering storage devices, and higher capacity communication systems. The signal and data processing instrumentation will have to be artificial intelligence/expert system-based. These systems will have to manage the limited bandwidth very efficiently.

## System Checkout, Calibration, and Test Ability

Throughout the discussions, the questions seem to lead to assurance testing, validation, testability, and maintainability. The general consensus was that Advanced Sensors and Instrumentation developers should be brought to the system design table at the start of the program and not as an afterthought. Testability and maintainability must be built into the original designs and facilitate calibration, check-out, and validation during operational phases.

## Summary

There were many good questions asked and discussions focused around typical engineering concerns:

- Increased reliability and accuracy for performance evaluation
- How to pre-flight, checkout, calibrate, and post-flight maintenance
- Reduce quantity to cables for data collection/sensor interrogation
- How to validate expert systems?
- Intelligent data reduction on-board

Most of the technical issues discussed are captured in the quad charts. Major contributors' on-going research areas are displayed in the appendixes.

SPACE TRANSPORTATION AVIONICS TECHNOLOGY SYMPOSIUM  
FLIGHT ELEMENTS

ADVANCE SENSORS & INSTRUMENTATION

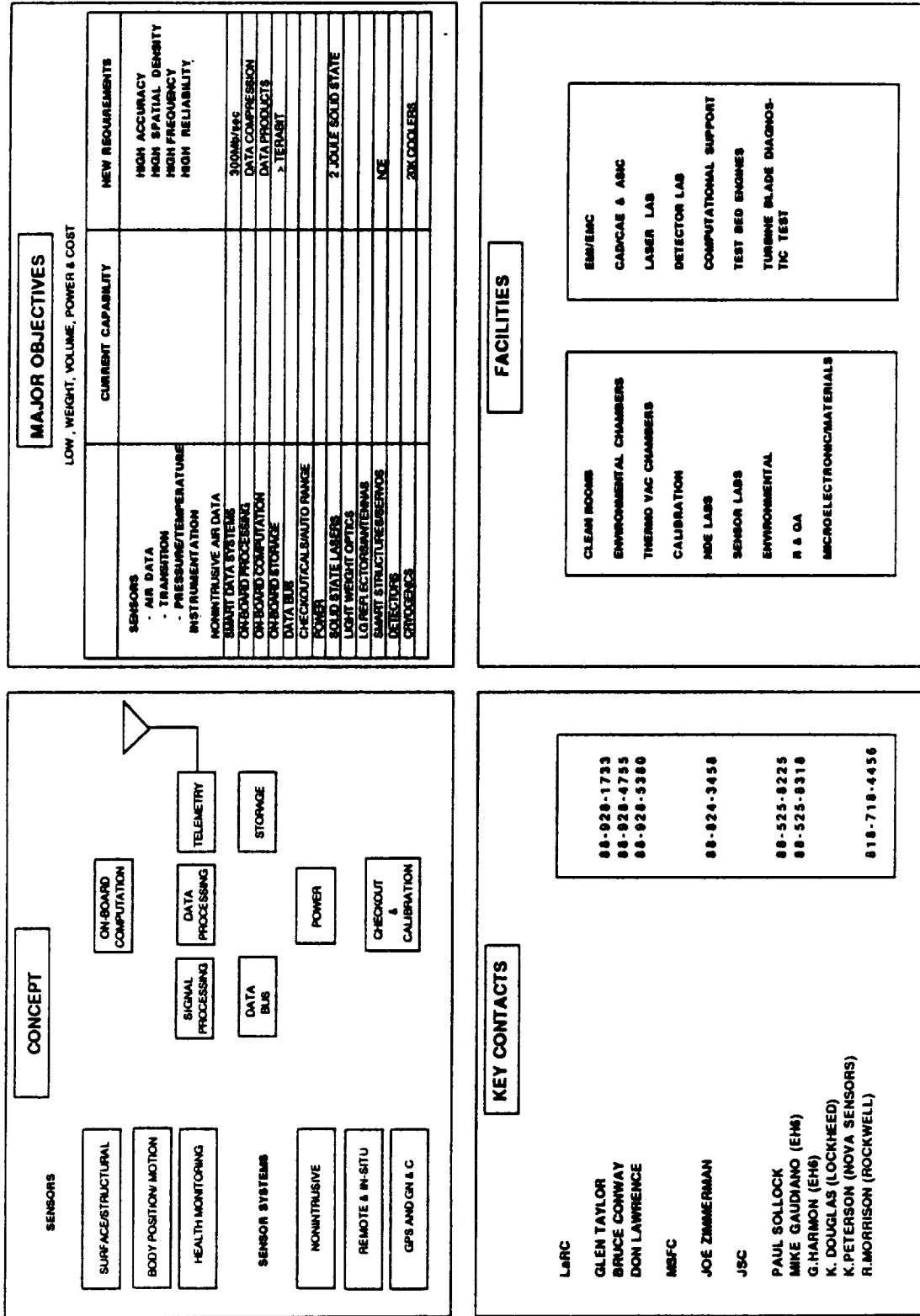


FIGURE 1



SPACE TRANSPORTATION AVIONICS TECHNOLOGY SYMPOSIUM  
FLIGHT ELEMENTS

ADVANCE SENSORS & INSTRUMENTATION

**TECHNOLOGY ISSUES**

- SMART SKINS - FIBEROPTIC TRANSDUCERS & TRANSMISSION LINES EMBEDDED IN ADVANCED COMPOSITES
- MICRO-MACHINED TRANSDUCERS - EMPLOYING CLASSICAL SEMICONDUCTOR PROCESSING TECHNIQUES TO BUILD MECHANICAL STRUCTURES & TRANSDUCERS
- SMART TRANSDUCERS - INTEGRATION OF A TRANSDUCER, SIGNAL CONDITIONERS, PROGRAMMABLE EMBEDDED MICROCONTROLLERS
- ADVANCED INSTRUMENTATION - INTEGRATION OF SMART TRANSDUCERS INTO A DISTRIBUTED BUS OR FAULT TOLERANT LOCAL AREA NETWORK (LAN)
- HYBRID ELECTRONICS & SURFACE MOUNT TECHNOLOGY
- INTEGRATION OF DIVERSE TRANSDUCERS & SIGNAL TYPES INTO SMART TRANSDUCER MODULE
- APPLICATION SPECIFIC INTEGRATED CIRCUIT (ASIC) DESIGN CAPABILITY TO MINIMIZE WEIGHT, POWER, & VOLUME PARAMETERS
- THIN FILM SENSORS
- HIGH TEMPERATURE STRAIN SENSORS
- SMART, MINIATURE & RELIABLE DATA ACQUISITION SYSTEMS (DAS)
- ON BOARD DATA PROCESSING
- ON BOARD COMPUTATION
- ON BOARD STORAGE
- ADVANCED DATA TRANSMISSION
- LASER-BASED RENDEZVOUS SYSTEMS
- 2 MICRON LASERS FOR EYE-SAFE AND WINDS
- LIGHT WEIGHT OPTICS FOR WIND SHEAR LIDAR
- CRYOGENICS - DEVELOP 20K COOLERS FOR SOLVING MOST DETECTOR PROBLEMS
- LARGE REFLECTOR ANTENNAS
- DEVELOP ELECTROMAGNETIC MEASUREMENT, MODELING, INJECTION & DETECTION SENSORS

**CANDIDATE PROGRAMS**

UPGRADE OF ORBITER MODULAR AUXILIARY DATA SYSTEM (MADS)

UARS

EOS

SHUTTLE C

SPACE STATION FREEDOM

ELV

MISSION TO PLANET EARTH

MANNED MISSION TO MARS

LUNAR BASE

**MAJOR ACCOMPLISHMENTS**

LIDAR

OPTICAL DISK

HIGH PRESSURE STAND ALONE PRESSURE MEASUREMENT DEVICE

OPTICAL PLUME ANOMALY DETECTION SYSTEM

**SIGNIFICANT MILESTONES**

90	91	92	93	94	GOALS
<b>SURFACE/STRUCTURAL SENSORS</b>					
DEFINITE REQUIREMENTS REVIEW TECHNOLOGY	▲	▲	▲	▲	○ SMART SENSORS
<b>HEALTH MONITORING SENSORS</b>					
DEFINITE REQUIREMENTS REVIEW TECHNOLOGY	▲	▲	▲	▲	○ SMART SKINS
<b>FLIGHT MEASUREMENT SYSTEMS</b>					
DEFINITE REQUIREMENTS REVIEW TECHNOLOGY	▲	▲	▲	▲	○ SMART, SMALL & RELIABLE DAS
<b>GOALS</b>					
○ ON BOARD DATA PROCESSING					
○ ON BOARD COMPUTATION					
○ ON BOARD STORAGE					
○ ADVANCED DATA TRANSMISSION					
○ SMART STRUCTURES					
○ LASER APPLICATIONS					
○ INTERFACE REQUIREMENTS DEF					
○ NDE					

FIGURE 2

# INTELLIGENT MATERIALS = SMART STRUCTURES

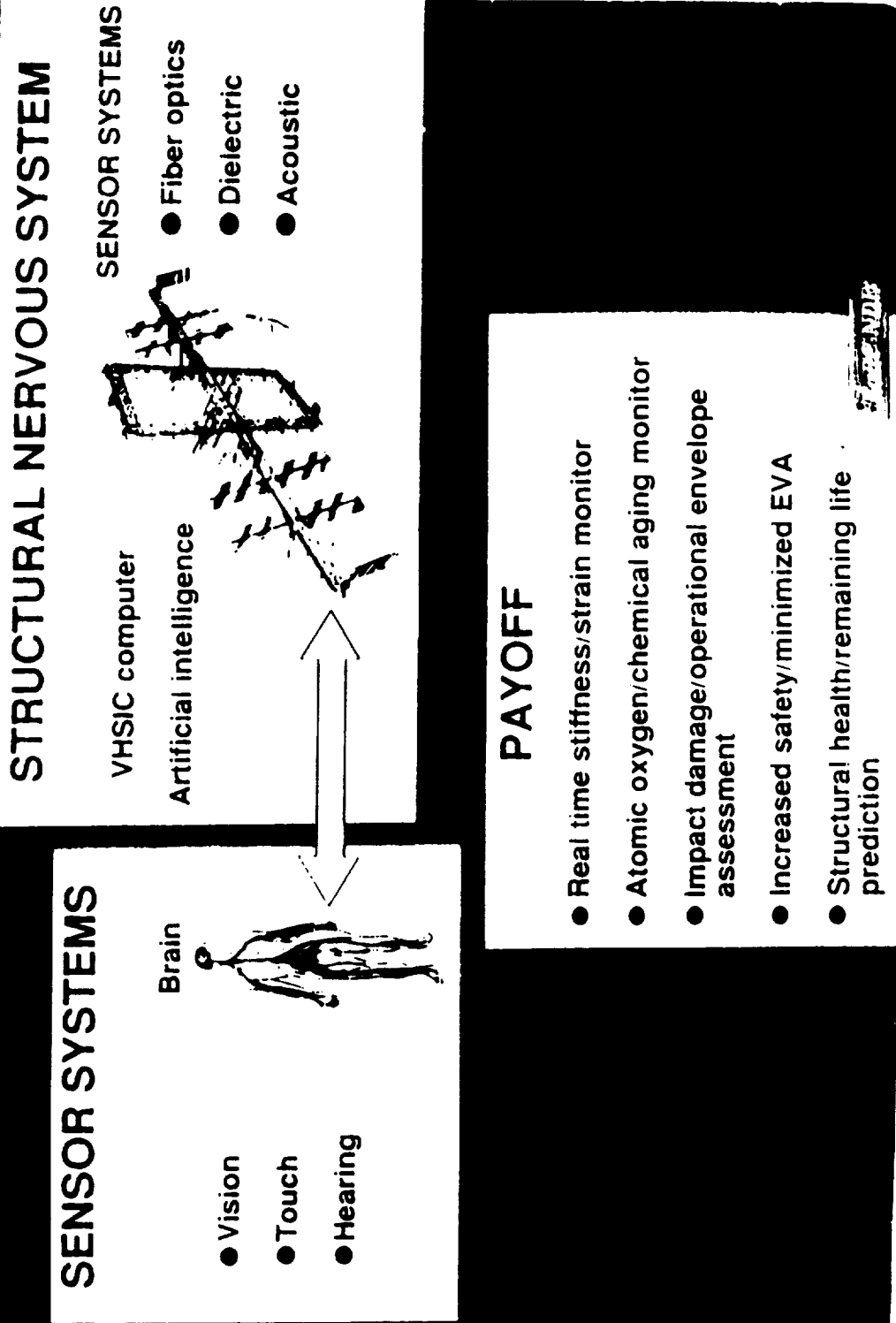
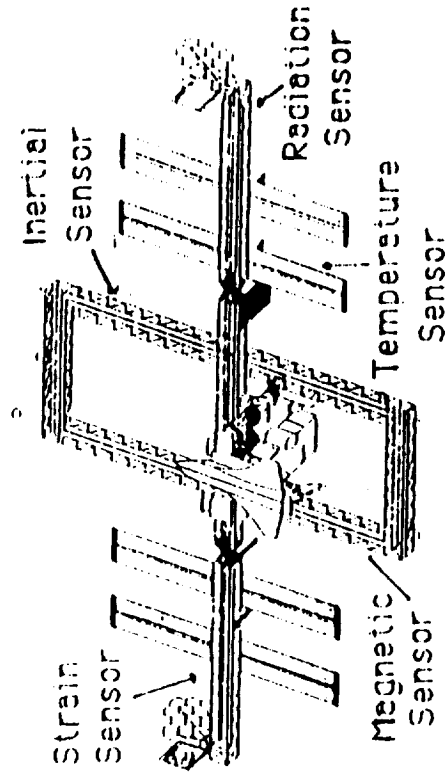


FIGURE 3

# FIBER OPTIC SENSORS



Space Station Requirements		Daily Requirements
Type	Purpose	Requirements
Linear	Magnitude	$7.5 \times 10^{-4}$ g
Acceleration	Frequency	1 to 4 hz
Strain	Magnitude	$2.5 \times 10^{-5}$
Level	Frequency	.1 to .5 hz

Theoretical Resolution Limits of Fiber Sensors	
Strain	$10^{-12}$ in/in
Magnetic	$10^{-12}$ Gauss
Electric	$10^{-4}$ V/M
Rotation	$10^{-5}$ Dg/Hr
Temperature	$10^{-8}$ Dg/C
Acceleration	$10^{-8}$ G'S
Acoustic	$10^{-5}$ Pa

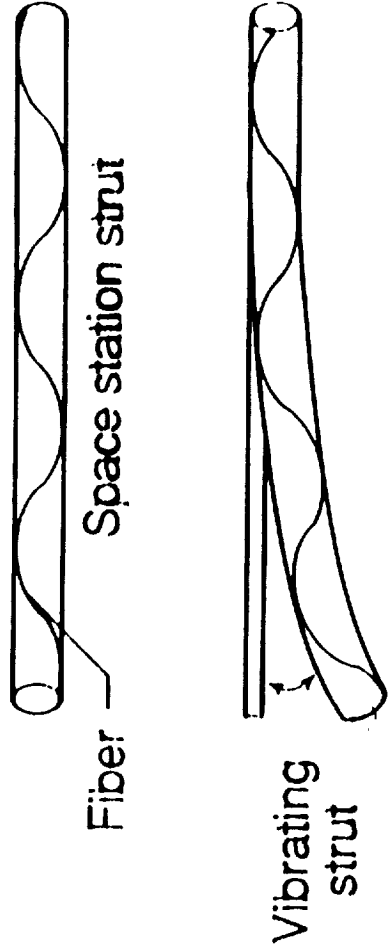
## Advantages Of Fiber Optics

High Bandwidth	0.1 To 100 Ghz
Small, Lightweight	50 To 500 um O.D.
Electrical Immunity	E. M. I., E. M. P.
Low Attenuation	0.2 To 5db/Km
Geometric Flexibility	

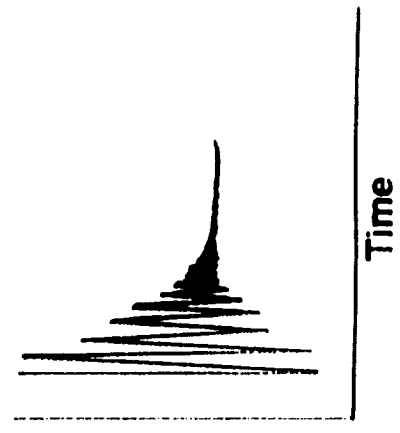
FIGURE 4

# FIBER OPTIC SENSORS FOR INTELLIGENT MATERIALS

- Benefits
- Low mass sensor
  - Integrated with structural material
  - No EMI
  - Distributed sensor
  - Multiple function fiber



Vibration data



FFT

Modal data

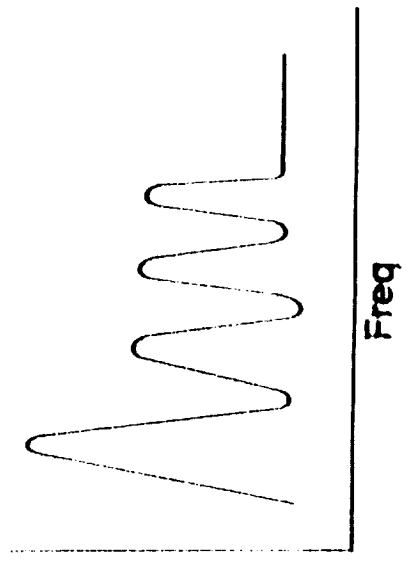


FIGURE 5

# NDE BY THERMAL DIFFUSIVITY IMAGING

## Advantages:

- Noncontacting
- Computer controlled
- Scans large complex geometries

## Thermal Relationships In Scanned Area

### Remote Measurement In Field Setting

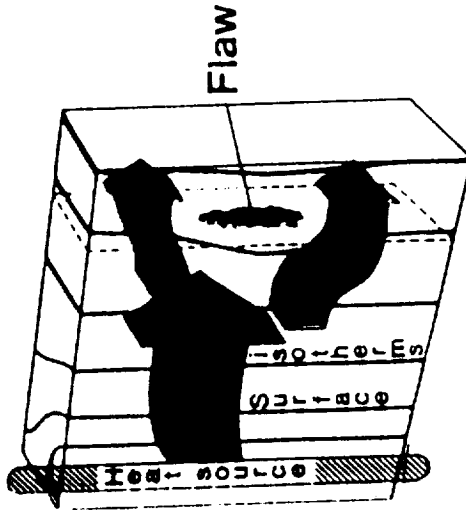
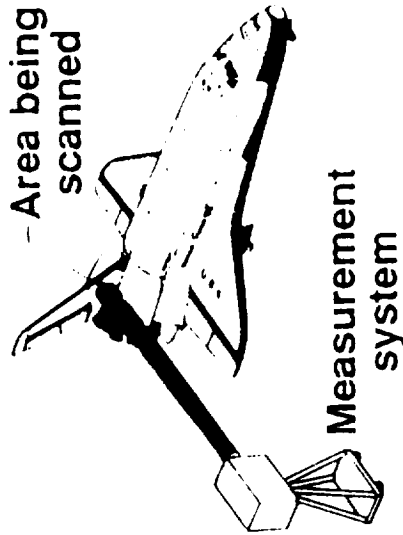
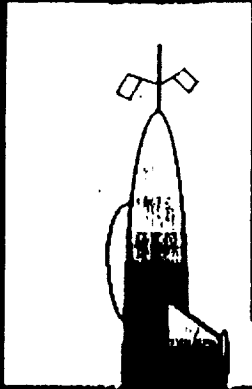
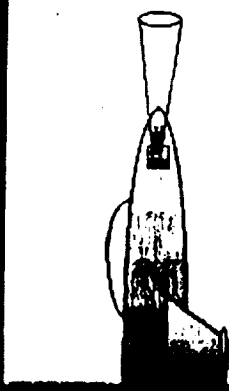


FIGURE 6

# LASER BASED AIR DATA SYSTEM



PITOT / STATIC PRESSURE  
 $\alpha/\beta$  VANES



LASER VELOCIMETER

- NON - INTRUSIVE MEASUREMENT OF SUPERSONIC /  
HYPERSONIC FLOW
  - AIR DATA
  - BOUNDARY LAYER STUDIES
  - CODE VALIDATION
  - ENGINE INLET FLOW FIELDS
- BUILD ON EXISTING DIAGNOSTIC STUDIES
  - SRA Inc., IRD, SANDIA, LOCKHEED/SANDERS,  
STANFORD
- FOCUS AIRBORNE LASER DEVELOPMENT CAPABILITIES  
TOWARD AIR DATA MEASUREMENTS
  - EXTEND LaRC WIND SHEAR LIDAR EFFORT

FIGURE 7

SOLID-STATE LASER SENSORS FOR SPACE EXPLORATION

- o THE SOLID-STATE LASER TECHNOLOGY BASE DEVELOPED FOR SATELLITE AND AIRCRAFT BASED ENVIRONMENTAL SENSORS IS IMPORTANT TO SPACE EXPLORATION
  - EXAMPLES OF ADVANCED SENSOR CONCEPTS FOR RENDEZVOUS/PROXIMITY OPERATION, LARGE SPACE STRUCTURES, PLANETARY SURVEYS
- o RENDEZVOUS/PROXIMITY SENSORS
  - LASER RADAR WITH DIODE LASERS/DIODE LASER PUMPED SOLID-STATE LASERS
  - IMAGE RECONSTRUCTION FROM LASER RADAR REFLECTIVE PROJECTIONS (CONCEPTS ADAPTED X-RAY ABSORPTION COMPUTER ASSISTED TOMOGRAPHY), COMPUTER VISION
- o LARGE SPACE STRUCTURE DISTORTION SENSORS
  - LASER RADAR WITH DIODE LASER/DIODE LASER PUMPED SOLID-STATE LASERS
  - SOLID-STATE LASERS WITH LONG FIBER OPTICS/FIBER LASER AMPLIFIERS AND/OR LOCAL LASER FIBER SENSORS
- o PLANETARY SURVEY SENSORS
  - SOLID-STATE LASER RADAR RANGING IMAGE RECONSTRUCTION
  - COMPUTER VISION, ROBOTICS NAVIGATION
  - WIDE WAVELENGTH RANGE TUNABLE SOLID-STATE LASER RADAR COLOR REFLECTOMETER, ROBOTICS

FIGURE 8

# HIGH PERFORMANCE REWRITEABLE SPACEFLIGHT OPTICAL DISK RECORDER

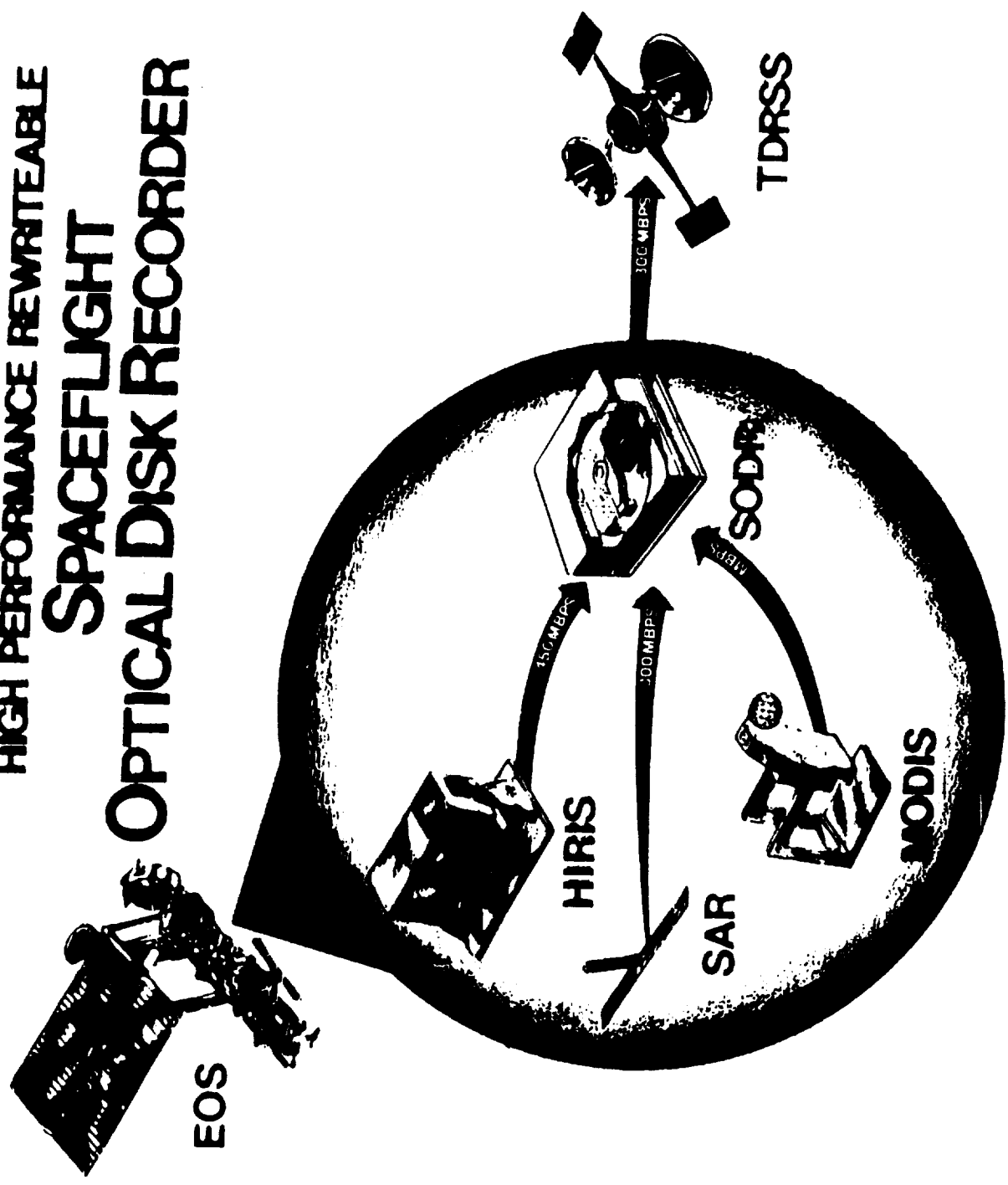


FIGURE 9



**APPENDIX 1**

**Kevin R. Douglas**

**Lockheed  
Engineering & Sciences Company**

## ADVANCED SENSORS & INSTRUMENTATION

### ADVANCED SENSORS & INSTRUMENTATION

Micro-gravity Transducers

Thin Film Transducers

Fiber Optic Transducers and Transmission Lines

Smart Skins: Fiber Optic Transducers and Transmission lines embedded in advanced composites;

Micro-machined Transducers: Employing classical semiconductor processing techniques to build mechanical structures and transducers;

Smart Transducers: Integration of a transducer, signal conditioning, programmable embedded micro-controllers;

Advanced Instrumentation: Integration of Smart Transducers into a distributed bus or fault tolerant Local Area Network (LAN);

Hybrid Electronics and Surface Mount Technology

### MAJOR OBJECTIVES

Low Cost

Low Weight

Small Volume

Low Power

Higher Accuracy: Local Signal Conditioning and Data Conversion

Self Calibration, Zero Offset, and Zero Drift

Function in Remote Locations and Severe Environments

Adaptable to future data processing requirements (Digital Input/Output)

Provides a technology base for next generation instrumentation systems

### KEY CONTACTS

R. Calloway/LaRC

M. Gaudiano/JSC EH6

G. Harmon/JSC EH6

K. Douglas/Lockheed

K. Peterson/Nova Sensors

### MAJOR MILESTONES

Review Technology (1990)

Establish Interface and Architectures

Define Hierarchy of Functions (1991)

Analysis and Demo in the Laboratory (1992)

### TECHNOLOGY ISSUES

Integration of diverse transducers and different signal types into a Smart Transducer Module

Radio Frequency Transmission, Fiber Optic Links, Infrared Transmission

Digital Input/Output Interfaces

Continued progress in Smart Skins (demonstration phase only)

Continued advances in micro-machining of transducers

Standards yet to evolve for Surface Mount Technology

### CANDIDATE PROGRAMS

Shuttle C  
Manned Missions to Mars  
Space Station Freedom  
Lunar Base  
Upgrade/Replacement of Orbiter Modular Auxiliary Data System (MADS)  
Components  
Stand-Alone Instrumentation Systems

### MAJOR ACCOMPLISHMENTS

Progress in Micro-Machined Transducers  
Demonstration of Smart Skins  
Surface Mount Technology and Hybrid Electronics  
High Pressure Stand-Alone Pressure Measurement Device (HP-SAPMD)

### SIGNIFICANT MILESTONES

Research and Technology Base  
Define Interfaces and Hierarchy  
Demonstration in Laboratory  
Detailed Test Objectives and Integration into Future Programs

**APPENDIX 2**

**Joe Zimmerman  
Marshall Space Flight Center**

**STATS - ADVANCED SENSORS & INSTRUMENTATION**

**KEY CONTACTS**

NASA	MSFC	W. T. Powers
NASA	MSFC	J. E. Zimmerman
NASA	LaRC	W. Nieberding
NASA	LaRC	G. Madzsar
NASA	SSC	G. Woods
AEDC		C. W. Darlington
Rocketdyne		S. Barkhoudarian
Aerojet		R. LaBotz
Pratt & Whitney		J. Baker
UTRC		R. Williams
NASA	KSC	W. Helms

**STATS - ADVANCED SENSORS & INSTRUMENTATION**

**MAJOR MILESTONES**

<b>Optical Plume Anomaly Detector</b>	<b>08/87</b>
<b>Infrared Gas Thermometer</b>	<b>03/89</b>
<b>Ultrasonic Flowmeter</b>	<b>06/89</b>
<b>Vortex Shedding Flowmeter</b>	<b>02/89</b>
<b>Non-Intrusive Speed Sensor</b>	<b>11/87</b>
<b>Fiber Optic Raman Thermometer</b>	<b>06/88</b>
<b>Nozzle Exit Plane Velocity Sensor</b>	<b>11/88</b>
<b>Thin-Film Sensors</b>	<b>08/89</b>

## General

Research and development programs are being conducted for improvement of sensors used on present Space Transportation Systems, providing sensors for current engine requirements where no practical measurement techniques are commercially available, and to assure availability of measurement technology to meet future Space Transportation Avionics System requirements. Benefiting programs will include the Space Shuttle Elements (SSME and SRB), Advanced Launch Vehicle, Orbital Transfer Vehicles, and long-duration space flights or exploration program.

## Earth-To-Orbit Propulsion Program

One group of research projects being conducted is under the Civil Space Transportation Initiative (CSTI) and specifically the Earth-To-Orbit (ETO) Chemical Propulsion program. The ETO program is a joint MSFC and LaRC effort with research projects being performed in-house and through outside contracts with other Government agencies, universities, and private industry. The emphasis of the ETO program is the continuing enhancement of knowledge, understanding, and design methodology applicable to the development of advanced Oxygen/Hydrogen and Oxygen/Hydrocarbon propulsion systems. Significant research activities in the ETO program are summarized in the following paragraphs.

An Optical Plume Anomaly Detector (OPAD) is being developed to view and analyze the SSME exhaust plume with the intent of obtaining information that would provide early indications of engine component degradation and/or precursors to a catastrophic engine failure. OPAD components include high resolution spectrometers and optical multi-channel analyzers. Testing of the OPAD during SSME engine firings at the Stennis Space Center (SSC) and at MSFC has been extremely successful and plans are being made to install ground-based OPAD systems at each test and launch facility. The potential of a flyable OPAD is also being investigated to provide input to a health monitoring system. An in-flight system could also provide information on normal engine component wear and possibly reduce the amount of disassembly and physical inspections of the engines after each flight.

Advanced cryogenic flowmeters are being developed for use on SSME class engines. Vortex shedding flowmeters have been designed and tested with promising results in some of the SSME ducts. Nonintrusive ultrasonic flowmeters are also scheduled for feasibility testing in the FY 90-91 time frame.

Other nonintrusive sensors under development for use on the SSME includes electromagnetic speed sensors for monitoring turbo pump speed, infrared hot gas temperature sensor for monitoring turbine exhaust temperatures, and a Raman backscatter thermometer for determination of temperature distribution within the pre-burners of the SSME. These sensors have successfully completed laboratory evaluation testing and are in the design phase for testing in an engine environment.

Solid-state and fiber optic based pressure sensors are being investigated for potential use on the SSME. These devices are being designed for direct mounting on cryogenic ducts to replace existing sensors which have to be off-mounted due to thermal sensitivity of the conditioning electronics.

Gaseous leak detection techniques are being investigated and developed for remote sensing of hydrogen leaks from space vehicle plumbing systems. Current sensing techniques are limited to point sensors which requires prior knowledge of the location of the leak or an extremely large number of sensors located around the vehicle to effectively quantify the leakage.

A nozzle exit plane measurement system is being developed for identification of species and flow velocity determination at the exit of the SSME nozzle. The system uses laser-induced fluorescence to tag molecules in the flow stream for processing to determine specie concentrations and velocities. The system is being developed for combustion code validations and engine performance analysis.

Thin film sensors are being developed for deposition on turbine blades and other engine components which require minimally intrusive diagnostics. Film deposition processes have been developed for measurement of temperature and heat flux on SSME turbine blades. Initial testing of instrumented blades has been accomplished on the Turbine Blade Tester at MSFC with promising results.

#### Solid Propulsion Integrity Program

Another group of research projects under the CSTI program are included in the Solid Propulsion Integrity Program (SPIP). The instrumentation development task is a sub-element of a Nozzles Technology effort monitored by MSFC. Instrumentation research includes investigations and development of new or advanced measurement techniques for use on or in composite materials of solid rocket motor nozzles. Emphasis is on high temperature, high response sensors for the measurement of temperature, strain, pressure, and stress in the composite materials. Tasks include investigation of attachment techniques and operational capabilities to the 1100°C temperature range for strain, stress, and pressure sensors. Fiber optic techniques are being studied for these applications. Attachment techniques include both surface mounted and embedded sensors. Another type sensor under investigation is a recession gage to measure erosion of the throat material during a motor firing. Sensors developed under the SPIP program will be tested and evaluated in the solid rocket motor test beds at MSFC.

#### Space Station Freedom Related

Three significant development projects are being conducted with applications on long-duration manned space ventures. All are involved with monitoring the atmosphere within a habitable enclosure.

An advanced Tandem Mass Spectrometer is being developed for trace contaminant monitoring. This spectrometer will reduce the time required to obtain a readout of the contaminant present from 30 minutes to 5 minutes, giving near real-time warning of hazardous conditions. The development effort is in Phase II of a Small Business Innovative Research (SBIR) program.

Another Phase II SBIR is being supported for the development of a Trace Atmospheric Carbon Monoxide Sensor. The objective is to develop a compact, sensitive CO sensor which is species selective and has low power consumption. The sensor uses a nondispersive infrared technique.



A Hazardous Materials Monitor (HMM) system is also under investigation for monitoring 5 groups of contaminants which might be found in a space station module. The groups are: metallic vapors; metallic aerosols; organic solvent vapors; gases, fuels, and combustion products; and etchants. The HMM will be used to sense inadvertent leaks of hazardous substances from experiments on-board Space Station Freedom and provide early warning for the crew to take appropriate remedial or evasive action. There is presently no other such monitoring system planned for the space station.

**APPENDIX 3**

**Rusty Morrison  
Rocketdyne International**

Advanced Sensor and Instrumentation development work at Rocketdyne and in the rocket engine world in general has been driven primarily by safety and maintenance considerations rather than control needs. The desire is to detect degradation in the engine in time to alter operation (shutdown or throttle back) to protect the crew and mission and/or diagnose condition, predict life, schedule maintenance, and support automation of ground operations. To these ends, studies dating back to 1980 have analyzed actual engine field operational recorded to determine historic degradation modes (example-89CA-079-41) and estimated current design and development information on current designs. These modes and the component most affected by them are summarized in table 89CA-079-42. Measurements have been identified at each stage of the degradation process and surveys of sensor technologies have been conducted to identify concepts with maximum payoff potential. Table 490-660A identifies the technologies currently under development for application to rocket engines.

Multi-disciplinary issues must be addressed in any sensor system concept. An integrated approach to system definition involves the engine system and component designers who define the measurants of interest and required data rates; the engine control system designer addressing functional distribution of processing, bus data rates, etc.; and the sensor design team itself which includes the sensor designer(s), the designer(s) of the part to which the sensor is mounted, associated stress, structural dynamics, thermal analysis, and the process physicist who relates the measurement of interest to what is recorded by the sensor. In the context of this integrated approach, smart sensors, in which the transducer itself outputs a digital data stream, optical sensors capable of easily integrating directly with fiberoptic data buses and tolerating extreme environments, and non-intrusive sensor technologies which don't penetrate pressure containers or interfere with the process being measured are current thrusts.

## ADVANCED INSTRUMENTATION TECHNOLOGIES AND PROGRAMS

Summaries are given below of representative advanced instrumentation technologies under development for rocket engine applications. Research referred to includes that being performed by Rocketdyne Instrumentation personnel under IR&D, SSME Technology Test Bed, and Orbital Transfer Vehicle Engine tasks.

The general goal of these efforts is to improve mission safety, confidence, readiness, and life cycle costs. Corollary goals are to accelerate turnaround times and to help reduce the "standing army" associated with between flight inspection and qualification of reusable engines. In addition, nonintrusive and/or nonprotrusive technologies are being developed to reduce the hazard associated with conventional measurement technologies or to provide valuable diagnostic data currently unobtainable because of hostile engine environments.

Several technologies developed for space transportation may be adaptable to manufacturing applications (e.g. leak tests and weld inspections). One of the underaddressed applications of advanced instrumentation for space transportation in general is its role in manufacturing processes. Focusing on monitoring and inspection capabilities over the entire life cycle of the system, from the start of manufacturing and throughout the system operating life, would provide the greatest gains in reduced life cycle costs and improved mission readiness.

No fundamental cultural changes at NASA seem necessary to support development of these technologies: numerous programs are initiated to support this development. Nevertheless, improved communication and coordination would be helpful between the different NASA divisions, between NASA and other Government agencies, and between NASA and companies developing or potentially using these technologies. This will provide a better bridge between the development of these technologies and their application in transportation systems. In this regard, accelerated funding is called for to allow timely implementation of the most promising of these technologies.

### Bearing Deflectometry

Description: A probe containing an optical fiber bundle is mounted in the engine with its tip in close proximity to the outside of a bearing race. Based on the intensity of light reflected from the race and back into the probe, minute deflections of the race surface are monitored at high frequency. This has proven in turbopump testbed applications to be a very sensitive indicator of bearing vibrations which can be correlated to bearing condition in real-time.

Programs: SSME Technology Testbed

Key Researchers: J. Collins and C. Martinez

Addressed Transportation Needs: Improved flight safety, accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

Time for Implementation Readiness: ca 1991

Relationship between technology development and transportation system development for this topic: Provisions for incorporation of the fiber optic probe(s) should be included in the engine design process. An historical database should be developed to quantitatively correlate bearing deflectometer signatures to bearing conditions in operating engines.

#### Isotope Wear Analysis

Description: Prior to engine assembly, a selected component is endowed with a low level of radioactivity on a portion of its surface. After assembly, the level of radioactivity is monitored between firings with a detector/analyzer operating externally to the engine. The loss of radioactivity is correlated to mass loss at the component surface with a resolution on the order of micrograms. The determined mass loss can be used to calculate remaining life of the component accurately without requiring engine disassembly.

Key Researchers: J. Collins, M. Randall, and S. Barkhoudarian

Addressed Transportation Needs: Accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

Time for Implementation Readiness: ca 1990

Relationship between technology development and transportation system development for this topic: Pre-irradiation of components requiring wear monitoring should be included as part of engine fabrication procedures. This will allow application of this nonintrusive technology.

#### Fiber Optic Turbine Blade Pyrometry

Description: A fiber optic probe is used to collect infrared thermal radiation from turbine blades as they rotate past the probe. This radiation is analyzed to determine temperature profiles of each blade in real-time. This information is used to identify small blade cracks which create hot spots, and other indicators of incipient blade failure.

Programs: SSME Technology Testbed, Reusable Rocket Engine Turbopump Health Monitoring Program

Key Researchers: J. Collins and M. Randall

Addressed Transportation Needs: Improved flight safety, accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

Time for Implementation Readiness: ca 1992

Relationship between technology development and transportation system development for this topic: Provisions for incorporation of the fiber optic probe should be included in the engine design process. A historical database should be developed to quantitatively correlate

pyrometer signatures to blade conditions in operating rocket engines.

#### Between-Flight Optical Leak Detection

Description: During between-flight inspection, an engine or other component is pressurized with an inert infrared-absorbing gas. The engine is illuminated with infrared light and monitored with an infrared camera. An infrared image of the engine, with leaking gas appearing as dark clouds in the vicinity of the leak, is provided by the infrared camera. Leaks from large sections of the engine are thereby monitored simultaneously and rapidly with high sensitivity (down to  $5 \times 10^{-4}$  scim). This technology is substantially more amenable to automation than currently used techniques for leak location and quantification. This would make possible system leak inspection times on the order of a few minutes. Current programs: SSME Technology Testbed, Rocketdyne Advanced Instrumentation IR&D.

Key Researchers: R. Delcher, M. Randall, and J. Maram

Addressed Transportation Needs: Improved flight safety, accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

Time for Implementation Readiness: ca 1990

Relationship between technology development and transportation system development for this topic: Qualification of an appropriate pressurant gas for optical leak checks should be part of the transportation system development.

#### In-flight (Propellant) Optical Leak Detection

Description: Optical methods are being developed for real-time detection, location, and quantification of propellant leaks in flight or in space. Among the methods being considered are light absorption/imaging techniques in the infrared or ultraviolet similar to the method described for between-flight leak detection. Other optical techniques, including Raman scattering, also show significant promise and are being investigated.

Key Researchers: R. Delcher, D. Gobeli, and J. Maram

Addressed Transportation Needs: Improved flight safety, accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

Time for Implementation Readiness: ca 1993

Relationship between technology development and transportation system development for this topic: Provisions for optical accessibility to external engine components would improve the effectiveness of this technology.

#### Remote Plume Spectrometry

Description: Light from rocket engine plumes is monitored with remote, ground-based optics. The light is analyzed spectrometrically to detect and

measure the quantity of molecular and atomic constituents in the plume. Such measurements have been made at Rocketdyne and at SSC in over a hundred engine test firings. These measurements are valuable tools in characterizing and distinguishing nominal and anomalous engine conditions. Furthermore, measured levels of several key plume constituents can serve as effective indicators of anomalous component wear and provide an early indicator of potential engine failure. For example, calcium-based constituents are characteristic of plume spectra from rocket engines such as the SSME, corresponding to nominal bearing cage wear. Plume spectra recorded in engine tests resulting in bearing cage failure have indicated substantial rise in these calcium-based constituents up to hundreds of seconds before redline detection and shutdown. Early detection of anomalous wear in nickel-alloy and copper components has also been accomplished by this means. Such diagnostics strongly suggest themselves as tools for early detection and minimization of failure damage.

**Key Researchers:** L. Wyett, J. Reinert, and D. Gobel

**Addressed Transportation Needs:** Engine characterization, improved flight safety, accelerated turn-around times, disassembly for cause rather than schedule, reduced life cycle costs, and improved mission confidence.

**Facilities in Use:** Rocketdyne Advanced Instrumentation Laboratory, Santa Susana Field Laboratories, and Stennis Space Center

**Time for Implementation Readiness:** ca 1991

**Relationship between technology development and transportation system development for this topic:** Provisions for optical accessibility to external engine components would improve the effectiveness of this technology.

### Ultrasonic Flowmetry

**Description:** An ultrasonic flowmeter is used as a nonintrusive means to measure propellant flow. A pair of ultrasonic transducers are mounted on a propellant duct. Ultrasonic signals are transmitted and received between the two transducers. The propellant flow velocity is determined by the frequency shift in the ultrasonic signals, in a calculation independent of propellant density and temperature. This flowmeter is designed to replace intrusive turbine flowmeters conventionally used in rocket engines. In the SSME Technology Testbed program, the ultrasonic flowmeter is being evaluated to replace the oxidizer flowmeter which was deemed unacceptable for the SSME and removed because of its intrusiveness.

**Key Researchers:** B. Szemenyei and S. Barkhoudarian

**Addressed Transportation Needs:** Engine characterization and improved flight safety.

**Time for Implementation Readiness:** ca 1991

**Relationship between technology development and transportation system development for this topic:** Provisions for mounting the ultrasonic transducers should be included in the selected duct design.

### Nonintrusive Speed Sensing

**Description:** An externally mounted, nonintrusive sensor is used to measure turbopump shaft speed. Measurements are made by detection of fluctuations in magnetic field at the sensor caused by the periodic passage of permanent magnets embedded in the turbo pump speed nut. This technology has been developed to replace the intrusive magnetic speed sensor formerly used on the SSME oxidizer turbo pump.

**Programs:** None currently funded (formerly SSME Technology Testbed)

**Key Researchers:** L. Wyett, J. Reinert, and S. Barkhoudarian

**Addressed Transportation Needs:** Improved flight safety and improved mission confidence.

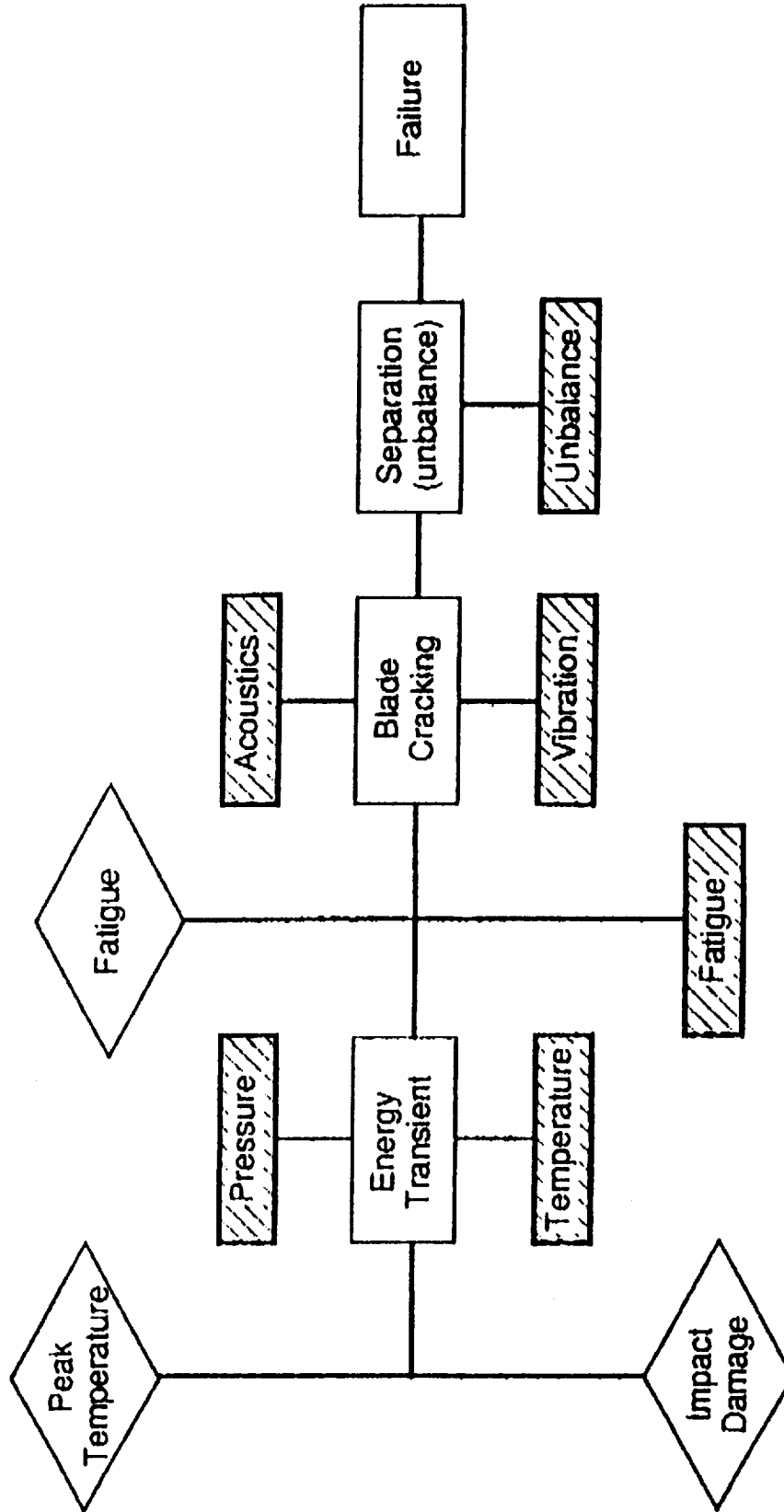
**Time for Implementation Readiness:** ca 1991

**Relationship between technology development and transportation system development for this topic:** In vehicles where this technology is to be used, provisions for incorporation of the magnets into the rotating assembly should be included in the engine design process.



# IDENTIFYING FAILURE MODE SIGNATURES

## Turbine Blade Failure



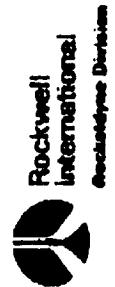
# FAILURE ANALYSIS

Failure Mode	Critical Components
Wear/erosion	Ball bearings, blades, injectors, posts, seals, seats, impellers
Fatigue	Blades, injectors, posts, bellows
Cracks	Blades, injectors, posts, bellows, welds, brazes
Leaks	Joints, welds, cracks
Leaks	Rotary seals, valve seats
Binding	Ball bearings
Spalling	Ball bearings
Blockage	Tubes
Thermal cycling	Blades
Foreign material	Combustion devices

# DIRECT CONDITION-MONITORING TECHNOLOGY PACKAGE

FAILURE MODE	TECHNOLOGY	CRITICAL COMPONENTS	BETWEEN FLIGHT			COAST OFF			IN FLIGHT			
			ISOTOPE	HOLD-GRAPHIC	PYROMETER	EXO-ELECTRON	ACOUSTO-OPTICAL	TORQUE-METER	PYROMETER	SPECTROMETER	DEFLECTOMETER	
WEAR/EROSION		BALL BEARING, BLADE, INJECTOR, POST, SEAL, SEAT, IMPELLER, LABY	X									
LEAKS		JOINT, WELD, CRACK		X								
BLOCKAGE		TUBE			X							
FATIGUE		BLADE, INJECTOR, POST, BELLOW				X						
CRACKS/DELAMINATION		BLADE, INJECTOR, POST, HOUSING, WELD, BRAZE, DUCT					X					
BINDING		SEAL, BEARING, LABY						X				
THERMAL STRESS		BLADE							X			
LEAK		SEAL, LABYRINTH								X		
FOREIGN MATERIAL		PLUME								X		
SPALLING		BALL BEARING										X
AVAILABILITY			C	P	C	P	P	P	C	P	C	C

C - COMMERCIAL, P - PROPRIETARY



490-860A

