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Rodney K. Bogue and Peter Erbland

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Rodney K. Bogue
Dryden Flight Research Facility
Edwards, California

Peter Erbland
NASP Joint Program Office
Wright-Patterson Air Force Base, Ohio

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PERSPECTIVE ON THE NATIONAL AERO-SPACE PLANE PROGRAM INSTRUMENTATION DEVELOPMENT

Rodney K. Bogue[*]
NASA Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523-0273

Peter Erbland[**]
NASP Joint Program Office
Wright-Patterson Air Force Base, Ohio

Abstract

This paper presents a review of the requirement for, and development of, advanced measurement technology for the National Aero-Space Plane program. The objective is to discuss the technical need and the program commitment required to ensure that adequate and timely measurement capabilities are provided for ground and flight testing in the NASP program. The paper presents the scope of the measurement problem, describes the measurement process, examines how instrumentation technology development has been affected by NASP program evolution, discusses the national effort to define measurement requirements and assess status of NASP technology; and summarizes the measurement requirements. The unique features of the NASP program that complicate the understanding of requirements and the development of viable solutions are illustrated.

Nomenclature

BTU	British Thermal Unit
CFD	computational fluid dynamics
CW	continuous wave
dB	decibel
FeCrAl	iron-chrome-aluminum
LIF	laser induced fluorescence
LOS	line of sight
NASP	National Aero-Space Plane
NDE	nondestructive evaluation
OH	hydroxyl radical (a combustion intermediary)
P	pressure
PdCr	palladium-chrome
PLIF	planar laser-induced fluorescence
$\dot{q}$	heat transfer
RF	radio frequency
SBIR	Small Business Innovative Research
SSTO	single-stage-to-orbit
T	temperature
Tech Mat	Technology Maturation
TMC	titanium matrix composite
h_c	combustion efficiency
h_m	mixing efficiency

* Aerospace engineer. Member AIAA
** Aerospace engineer. Member AIAA.

Introduction

Instrumentation for the National Aero-Space Plane (NASP) program, is an enabling technology critical to accomplishing the program goals. This paper provides: (1) an historical overview of the work within the NASP program to develop instrumentation technology in support of the program objectives, (2) a discussion of the development process and activities, (3) an assessment of the current development status, and (4) a perspective on the features of the NASP program that contributed to the current state of instrumentation technology readiness.

Defining the Measurement Problem

In the NASP program, instrumentation development is seen almost exclusively as a problem in developing transducers to measure the key parameters necessary to confirm performance and research models of physical phenomena. There are additional aspects to the instrumentation task, such as data acquisition, system interconnects (wiring or fiber optics), recording, and telemetry. However, the program technology needs were thought to be concentrated on the development of transducers that would operate in the extreme environment characteristic of hypersonic atmospheric flight.

Scope of the Measurement Problem

In this document, the measurement problem has three essential domains. These are quality, environment, and application. These domains or dimensions are illustrated in Fig. 1.

Quality

The quality domain characterizes the quality of the information available. Defined here, quality is a multidimensional domain that includes the factors normally associated with the goodness of information. Typical quality factors are repeatability, accuracy, precision, and frequency capability. Off-the-shelf systems provide adequate measurement quality information under benign environmental conditions. For new measurements, the measurement quality must be established from new concepts with new baseline standards defined simultaneously. For example, when a thermographic phosphor technique is used for temperature measurement, the phosphor measurement repeatability, accuracy, precision, and frequency response must be established by experiment. This capability then becomes the baseline standard for thermographic phosphor temperature measurement.

Environment

The environment domain encompasses all the environmental factors that influence the measurement. In the NASP program, the primary environmental factors are severe temperature and high heat transfer rates. Other environmental factors include: oxidizing–reducing atmosphere, ionized–plasma gas conditions, low temperature (liquid–slush hydrogen), high thermal gradients, and high-intensity acoustic fields.

Application

The application domain includes the details of making a specific measurement in a specific situation. The application domain is characterized by the need to integrate transducers into the NASP systems, whether structural, propulsive, or aerodynamics. Often, the integration requires that the transducer be small. In others, it may need to be chemically nonreactive, or the transducer installation may require matching some physical parameter, such as thermal conductivity or specific heat, so the parameter being measured is not disturbed. Most situations require a combination of these factors to meet the specific need. The location of the test in either the ground or flight environment is also a factor in the application domain. The following examples illustrate the application domain; however, these examples are not fully representative of the broad spectrum of unique applications in the NASP program.

The first example is making a heat transfer measurement on the surface of a highly curved wing-leading edge of a vehicle in hypersonic flight. This measurement must be performed without adding surface roughness, and without disturbing the surface heat conductivity or thermal capacity. This application requires that the transducer be integrated into the leading edge and the means for transmitting the information away from the transducer (wiring or fiber optics) must be imbedded into the supporting structure. The sensing for this application may also be possible through remote, nonintrusive techniques. This application is far more difficult to implement than a ground test involving heat transfer measurement from a flat surface, for example.

The second example is making a measurement of the gas species in a scramjet propulsion system. This must be done in the limited volume available in a flight vehicle while providing optical access for the laser beam probe in the extreme thermal environment. A similar measurement in a laboratory test facility would not impose the severe size constraints on the measuring equipment, although the quality and environment domains would be nearly the same for both situations.

For the NASP program, measurement technology is adequate to satisfy the quality domain requirements for benign environments. However, the environmental and application domains are inadequate, and development is continuing to establish improved capability. This situation is shown in Fig. 2. The quality domain is coupled to the environmental and application domains in the sense that adequate technology for benign environments is not adequate technology for extreme environments and special application situations.

Quantifying the Measurement Domains

The three measurement domains provide useful standards to gauge current measurement capability and determine instrumentation development requirements. However, to use these standards, it is first necessary to quantify each of the three domains. The quality domain is more difficult to quantify than others because the quality requirements are determined by the objectives of a particular test, whereas, the environment and application requirements are determined by the test article and test conditions. This link between measurement quality and test objective is less intuitive than the connection between either environment and test conditions or application and test article.

Uncertainty analysis defines the relationship between test objectives and measurement quality. Uncertainty analysis takes the specific, quantified, test objectives and establishes the type, location, and quality of measurements needed. For example, a ramjet combustor test is planned to determine combustion efficiency for a new fuel injection concept. To be successful, the combustion efficiency must be determined to an accuracy of ± 5 percent. An uncertainty analysis examines the equations used to calculate combustion efficiency (h_c) from measured facility and test data. This allows the sensitivity of h_c to each measurand to be defined. Subsequently, the expected accuracy of each measurement (P, T, $\dot{q}$) is propagated through the performance equations to determine the expected accuracy of the combustion efficiency. The accuracy required of the various measurements can then be adjusted to meet the required accuracy in combustion efficiency. This analysis allows a quality requirement to be established for each measurement, and justifies that quality as being necessary and sufficient to accomplish the objectives of the particular test. Unfortunately, uncertainty analysis is complex, time consuming, and difficult to generalize and for this reason, the measurement quality dimension is difficult to bound.

For the NASP program, the quality domain is especially difficult to bound because of the diversity of test objectives, the rapid evolution of test techniques, and the lack of uncertainty analyses for specific tests within the program. Consequently, the quality domain, where it has been bounded, is a somewhat general and artificial estimate of the expected quality requirements. The environment domain is bounded by the thermal, chemical, mechanical, and acoustic environments in which the vehicle is designed to operate. The application domain is bounded by the variety of material systems and structural concepts under development as well as the overall weight, volume, and power limitations for the instrumentation on the X-30. These issues will surface again when the challenge of requirements definition is discussed.

Measurement Process

Measurements are made by using a physical phenomenon to transform information into a usable form. The transducer is subjected to the effects of a measurand of interest and the transducer output provides the useful information (Fig. 3). “All transducers respond to all aspects of their environment in all ways of which transducers are capable of responding...”[1] For example, the transducer responds to the thermal, electromagnetic, chemical, and mechanical environment. The challenge of measurement is to enhance the desired response(s) and to suppress the undesired responses. An example of a strain transducer is shown in Fig. 4.

Thermal Effects

The thermal environment amplifies the intensity of the other responses in addition to inducing its own effects. Change in physical characteristics of materials is a major effect of temperature. Temperature changes affect stiffness, yield strength, and creep. The following example shows how the other responses are intensified. At room temperature, the chemical effects of oxidation on the sensor and installation are negligible for the operating lifetime of most installations. At elevated temperatures, oxidation may shorten the useful lifetime to a few hours and require special recalibration procedures to accommodate the change in chemical composition. Another example is the thermal environment that precipitates changes (reversible or irreversible) in the physical state of transducer components. Examples of state changes include changes in physical strength because of temperature changes or because of the formation of new compositions (such as alloys) created by nearby components. The effects from new compositions tend to be irreversible.

Chemical Effects

The chemical environment precipitates chemical changes in the makeup of a transducer and its installation. These changes cause degraded performance. A common example of this effect is the oxidation of critical materials that irreversibly change the physical characteristics over time to produce “aging”. Besides oxidation, chemical interaction between transducer components is a factor that must be considered especially when the device is operated at elevated temperature. Special coatings can sometimes be used to separate reactive materials and alleviate the effects of chemical degradation.

Electro-magnetic Effects

The electro-magnetic environment introduces spurious signals into the transducer outputs through electromagnetic fields near the transducer. Sources of these fields include power wiring, power conversion components, and various radio frequency (RF) transmissions. In hypersonic flight, the local flow field about the vehicle reaches temperatures where ionization and dissociation create a conductive plasma condition, the effects of which are not well understood.

Mechanical Effects

The mechanical environment includes the absolute and differential physical motions to which the transducer is subjected. These motions include acceleration, velocity, and displacement as well as differential versions of these same parameters. Mechanical strain is a common example of a differential displacement being experienced by a transducer. The effects of transducers subjected to mechanical strain may include changes in offset, scale factor, and linearity. If the transducer is not irreversibly damaged by the strain, recalibration is usually required at a minimum.

Transducer Example

The typical strain transducer uses piezo-resistive effects and sensor distortion to provide an output that changes resistance in response to mechanical strain inputs. Figure 4 illustrates the transducer response situation with several environmental stimuli being applied to the strain transducer. A useful strain transducer will enhance the response to the mechanical environment and suppress responses to all other environmental stimuli.

The typical strain transducer response to the previously mentioned environments will be assessed in the following paragraphs. If the response is manifest as a change in the basic transducer characteristic (resistance), the response will be termed intrinsic. Extrinsic response is the result of effects associated with attachment to the structure. When the strain transducer is installed, the effects of this installation modify the transducer behavior and the strain at the installation point. Strain transducers respond to the thermal environment with a change in intrinsic resistance because the electrical resistance of most materials changes as the temperature changes. Over wide temperature excursions, many materials exhibit phase changes in their crystal lattice structure. A phase change often interjects a step change in resistance at a critical temperature. When a transducer material is an alloy at elevated temperatures, one of the alloy constituents may sublime and change the transducer makeup thereby altering the intrinsic electrical resistance and the response to the applied strain. Constituent sublimation is seen as a drift in the intrinsic resistance.

Thermal effects also appear in the gauge attachment to the measured structure. When the structure and the strain transducer have different thermal coefficients of expansion, a strain will be induced into the transducer because of a differential expansion as temperature changes. This effect is in the extrinsic response category and is often conveniently combined with the intrinsic responses previously noted into a term called apparent strain. A strain gauge installation can be temperature cycled to calibrate the response to temperature and the calibration used to suppress the effects of temperature during actual strain measurement. Figure 5 shows that the magnitude of this effect for commercial gauges employed under NASP can be as high as 14000 μ strain for anticipated temperature cycles. Through the use of temperature compensation techniques, this 14000 μ strain may be reduced to less than 4000 μ strain (also shown in Fig. 5). These techniques were developed as a part of the NASP instrumentation development activity. This gauge output variation must be applied as a correction factor to the measured strain value which may be typically between 100 and 2000 μ strain. For quality measurements, the apparent strain variation with temperature must be highly repeatable.

The chemical environment affects the intrinsic and the extrinsic responses of the strain transducer. The intrinsic response is caused by changes in the chemical makeup of the transducer itself (usually experienced as oxidation). Often an alloy constituent of the transducer will oxidize at high temperatures and change the basic gauge resistance and the basic response to strain. These effects are similar to those experienced when an alloy constituent evaporates. This response would be seen as a slow change in gauge characteristics that are combined in a term called drift or aging.

When the strain transducer is installed, the installation modifies the strain transfer and the strain at the installation point. The gauge installation modifies the strain when the structure lacks stiffness and the gauge installation adds stiffness at the point of measurement. This situation frequently occurs when the strain must be measured in a thin skin.

Development Time and Resources

Substantial work is required to transform a new measurement concept into a useful research tool. This work translates into significant time and resources. Experience has shown that this process requires several million dollars and between 5 and 10 years to accomplish.

Program History

To understand the state of NASP instrumentation requirements and technology development it is necessary to first understand the history of the NASP program and the evolution of the instrumentation program.

Copper Canyon (1983–1985)

The NASP program began in 1983 with the “Copper Canyon” phase which concentrated on vehicle concepts. This stage of the program was completed at the end of 1985. There is no evidence that any measurement development work was done during this program phase.

Technology Maturation (1986–1990)

Phase 2 of the NASP program began in 1986. The early years of this phase were marked by competitive engine and airframe development efforts and the formation of the Technology Maturation (Tech Mat) program to develop critical technology required by the NASP program. Technology teams were formed to direct technology advancement in the following seven disciplinary areas: aerodynamics, computational fluid dynamics (CFD), high-speed propulsion, low-speed propulsion, structures, materials, and flight systems. Government staff provided the direction for these teams with participation and periodic review by contractor and other government and academic representatives. Responsibility for instrumentation development was placed within these seven teams. Two teams (structures and low-speed propulsion) identified funding to support measurement technology development.

Shortly after the teams were formed, an instrumentation task force was established. Near the end of the Tech Mat program the Instrumentation Task Force was formally chartered as an instrumentation team and resources were provided for additional development covering multidisciplinary instrumentation problems such as high-temperature optical fibers and optical fiber-based sensing. By the end of the Tech Mat program, five of the original seven teams had initiated measurement technology development primarily concerned with ground test measurements.

Consortium–National Team (1990 to present)

In 1990, the five NASP prime contractors formed an instrumentation consortium. This group focused on developing needed technology to support NASP flight measurements. Shortly after the consortium began work, competition ended, and the five prime contractors formed the national team. Consortium activities and the Tech Mat program ended about this same time. When the national team was formed, work was allocated to each of the participating contractors as work packages. Several contractor work packages were identified to continue instrumentation development, however, because of resource allocations, only the three airframe contractors participated in this development. Coincident with this teaming, the government work package process was created to complement the contractor's activity and to continue the government contribution within the technology program. Work package oversight was provided by a consolidated government–contractor review team.

The Challenge of Requirements Definition

From the outset of the NASP program, development of measurement requirements has been a significant challenge. The reasons for this are programmatic and technical, yet the results are the same; a more generalized definition of measurement requirements, a more general statement of measurement deficiencies, and a less focused technology development program. The following paragraphs briefly relate the programmatic and technical features of the NASP program that have particularly complicated the definition of measurement requirements.

Programmatic Challenges

The development of measurement requirements for NASP has been complicated by several programmatic factors. These factors include cooperation from the disciplines, program organization, evolution of the vehicle design, competing program objectives (research vs. demonstration), schedule fluctuations, and the lack of clear payoff toward achieving program goals.

Disciplinary Cooperation

Since the disciplinary engineers (structures, aero, propulsion) represent the customer, their cooperation is essential to development of credible measurement requirements. Obtaining a clear set of requirements from the disciplines, i.e., what they must measure, as opposed to what they desire to measure, has been difficult. The disciplines have for the most part, only identified measurement requirements that could be satisfied with off-the-shelf instrumentation.

Program Organization

In the beginning, the program was not organized to advocate and address measurement requirements. Attempts were made to improve requirements definition as the program gained momentum. This included chartering the instrumentation task force, the subsequent formation of an instrumentation team, and the formation of the instrumentation consortium.

Evolution of Design

The evolution of the NASP design also contributed to the problem of defining valid requirements. The wide range of structural concepts, material systems, engine concepts, and ground test methods created many environments and applications within which measurements could be required. For example, a measurement such as heat flux had to be considered for each of the possible material systems with their corresponding unique thermo–chemical environments and structural design concepts [copper alloys, graphite–copper composites, refractory metals (coated or clad), cobalt and nickel superalloys, titanium matrix composites, beryllium and beryllium composites, carbon–carbon, and carbon–silicon carbide]. This situation has improved because the number of material systems and design concepts have been reduced as the program has evolved.

Competing Program Objectives

Measurement requirements definition has been affected by the uncertainty over whether the X-30 vehicle is a research test bed or a demonstration vehicle for single-stage-to-orbit (SSTO). This competition extends to the ground test program wherein many of the tests must be a balance between research, to understand the behavior of a component, and demonstration to prove that a given technical approach will work. Satisfying the research community implies higher measurement accuracy and more difficult measurands (e.g., wall shear, flowfield properties, and surface strain) versus the demonstration community whose primary measurands are those required for system control and safety (e.g., surface pressures, and temperatures). In programs of this type, it is important to establish early on the emphasis (research, demonstration, or some balance between) which will guide the test objectives and consequently the test requirements.

Schedule

The aggressive, success oriented program schedule created the dichotomy that if the instrumentation needed by the program took more than 1 to 2 years to mature, it was already too late for development; on the other hand if the development only required 1 or 2 years, then it could be delayed until the next phase of the program. Thus, a serious effort to define the measurement requirements and provide for development of the needed technology could be delayed.

Lack of Payoff

Clear requirements are necessary to understand deficiencies, which in turn will show the payoff of investing in measurement technology. In particular, the lack of data quality requirements made advocating development work substantially more difficult. If this data quality assessment were accomplished, the payoff in understanding measurement requirements and the benefits derived from instrumentation development would be clear.

Technical Challenges

In addition to the programmatic challenges, there are unique technical features of the NASP program that have complicated the definition of measurement requirements. The most important issues include parallel technology development, differences in ground and flight requirements, the variety of applications and environments, the complexity of the transducer integrations, collective severity of the measurement environments, and the lack of sensitivity–uncertainty analysis. Each issue will be discussed in the following paragraphs.

Parallel Technology Development

The basis for these factors is the parallel technology development required to satisfy NASP design goals. Figure 6 illustrates the number of technical fields under development by NASP and compares this with earlier experimental hypersonic vehicles. By way of example, the NASP program is conducting basic research to characterize the thermal and mechanical properties of several advanced materials. Concurrently, the manufacturing processes for these new materials are under development to understand the optimal methods for fabricating cost effective materials of uniform quality. In addition, the NASP program is developing advanced structural concepts using these materials. This parallel development increases the scope of the measurement requirement (measurement capability for multiple candidate material systems and structural concepts) and complicates the solution of any single measurement problem.

This increased complexity is shown by taking a single material–structural concept (titanium matrix composite (TMC) hot structure) and considering a single measurement (strain). We define the measurement environment as a silicon-carbide fiber reinforced b-21S titanium composite material system, consolidated using a hot isostatic press process, joined using either spot welds or brazed joints and intended for operation to 1500 °F. The measurement of strain on such an article is complicated by (1) the poor behavior of conventional strain gauges between 700–1500 °F (nonlinear, nonrepeatable apparent strain; temperature dependent drift and gauge factor; and immature attachment techniques), (2) lack of maturity of the TMC thermophysical properties database, (3) batch-to-batch variability of the fabricated materials, (4) complex, thermal-cycle-dependent, residual stress state of the composite (a function of its processing and lay-up), and (5) the variable performance of the developmental structural attachment–assembly processes.

The resulting complexity of strain measurement given this host of problems seems obvious when seen collectively from the instrumentation perspective. However, it is often overlooked when viewed from the isolation of any single discipline. This is only one of the measurement problems presented by the parallelism in NASP technology development. Clearly defining the measurement problem for each measurement given the variety of NASP materials and structures presents a daunting challenge.

Ground versus Flight Requirements

The need to define the unique measurement requirements for ground and flight testing further complicates the requirements development process. Although the measurands required are similar, the constraints imposed on meeting those requirements can be different (Fig. 7). Thus, clear definition of these constraints is necessary to structure an adequate development program.

Variety of Applications

A given measurement must accommodate many applications. For example, Fig. 8 shows that the problem of defining heat transfer measurement requirements is complicated by the need to make these measurements in seven different materials for four different structural concepts, each of which constitutes a unique application. Each application is designed to accommodate a different vehicle thermal, mechanical, and chemical environment. In addition, several transducer concepts must be considered to identify the approach that will best satisfy the measurement quality, environment, and application requirements.

Complexity of the Transducer Integrations

The complexity of NASP structural designs, the severity of the test environments, and the difficulty and risk associated with transducer integration have hampered the development of measurement requirements. The vehicle design must be tailored to accommodate critical instrumentation installations. For example, when a critical structural member has an upper temperature limit beyond which failure is highly probable, a means must be provided to measure and monitor that temperature even though it may require a design modification. In this situation, there are no workarounds. A high degree of design integration is required to ensure that a transducer installation approach will satisfy the measurement requirement yet not compromise the structural integrity.

The complexity of the transducer integration problem coupled with the rapidly evolving structural design space has resulted in the first priority being placed on the demonstration of survivable structures. The additional complications presented by embedded instrumentation will be addressed only after survival is demonstrated. This approach significantly complicates the application dimension of the measurement requirements. Figure 9 illustrates the type of cooled panel structure required for an SSTO vehicle. Clearly pressure, temperature, heat flux, and wall shear measurements within a 0.020-in. wide structure present formidable sensor integration challenges.

Diversity of Measurement Environments

The NASP program has a significant range of environments within which measurements must be accomplished (Fig. 10). These environments are directly related to the maturity of the vehicle design and database. Thus, as the design (geometry or materials), target operating conditions (dynamic pressure), or fidelity of the test and analysis database change, the measurement environments change. For example, as the understanding of shock-enhanced heating has evolved, the projected peak heat transfer rate, where the bow shock intersects the engine cowl leading edge, has spanned the range from 50,000 to 90,000 BTU/ft^2-sec. Similarly, the peak acoustic levels predicted for the vehicle have varied from 170 to 200 dB. This variability forces the generalization of the measurement environment requirements to have stable objectives for the measurement development activities.

Sensitivity and Uncertainty Analysis

The development of credible measurement requirements has been made more difficult by the lack of sensitivity and uncertainty analyses. The objective of these analyses is to understand the type of measurements and the measurement quality required to satisfy the objectives of a test. The alternative is to gain this insight empirically by the costly process of trial and error. The importance of this point is shown by the decision to develop hydroxyl radical (OH) nonintrusive diagnostic systems for high-speed combustor testing.

The NASP program has invested substantial resources to develop two nonintrusive systems to measure OH. This decision was based on several logical premises all of which strongly suggested that OH was a viable indicator of combustor performance. When the systems were used in combustor testing, the OH images were difficult to interpret, could not be quantified, and most importantly, could not be used to establish or absolute combustor performance. Therefore, this diagnostic was limited to providing qualitative insight into combustor flows.

A numerical sensitivity analysis was conducted for the combustor after it was found that the data produced by these systems were not providing the required insight. Mixing was varied ±10 percent that produced a +14-percent/–11-percent change in the combustion efficiency. The various surface and flowfield quantities were examined to determine their relative change compared to that seen in the mixing and combustion efficiency. Figure 11 shows the measurands that are useful for determining combustion efficiency for a data plane at the combustor exit. It is clear that OH is not a change-sensitive indicator for combustion efficiency, because it decreases from the nominal value whether the mixing is increased or decreased. Conversely, the mass flux of water and the line-of-sight (LOS) averaged water number density vary in direct proportion to the combustion. Note also that oxygen mass flow is a sensitive indicator of combustion efficiency for the case analyzed. An important fact not revealed by this data presentation is that for this analysis, less than 5 percent of the original oxygen remains in the flow at the exit plane. Therefore, a moderate change in combustion efficiency produces an unusually large percentage change in oxygen mass flow. The accuracy of the measurement is a critical consideration if changes in small quantities must be resolved, as would be the case for measuring oxygen in a stoichiometric or rich combustor with high-combustion efficiency.

The conclusions drawn from this sensitivity analysis are (1) water and oxygen are better indicators of combustor performance than OH for high-speed combustor testing, and (2) sensitivity analysis should be followed by an assessment of the accuracy with which each of the candidate parameters must be measured. Thus, sensitivity and uncertainty analyses are key tools in defining and validating measurement requirements, and in the creation of instrumentation development programs to address measurement deficiencies.

Requirements Status

It is difficult to delineate specific measurement quality, environment, and application requirements for the large number of unique measurements required by the NASP program. Measurement requirements, like any other requirements, must be supported in the management process by a spokesperson backed by substantiating information derived from test objectives. Test objectives cannot be solidified until the evolution rate of the design reaches the point where the environmental and application requirements are bounded. Measurement quality requirements for the ground and flight test activities must then flow from uncertainty and sensitivity analyses.

Despite the uncertainties and generalities inherent in the development of measurement requirements for the NASP program, several major efforts have been mounted to understand these requirements. These efforts were made by the Instrumentation Task Force and the Instrumentation Consortium which were introduced earlier.

Task Force Assessment

The instrumentation task force assessed the measurement requirements for structures, propulsion, flight systems, and aerodynamics disciplines. The measurement needs were evaluated based on priority, schedule, and measurement technology maturity. Within each category, the task force provided a separate evaluation for ground testing and flight testing. This evaluation identified 26 areas requiring development emphasis, 20 specific measurands and 6 broadly defined technologies (Fig. 12). This assessment guided the early investments in instrumentation development and was the basis for the next requirements assessment.

Instrumentation Consortium Assessment and Flight Measurement List

Instrumentation development conducted under the NASP Tech Mat program was primarily aimed at ground test measurement deficiencies. However, flight instrumentation deficiencies were seen as potentially long poles in the X-30 development path and therefore, more effort was needed to attack the most critical of these problems. In response, the five competing NASP contractors formed the instrumentation consortium to collaborate in the development of required flight instrumentation. The contractors revised and prioritized the instrumentation task force measurement list into 18 measurement areas. Eleven of these measurement areas were selected for treatment in the consortium.

The first task in the consortium program was to evaluate the flight measurement requirements for each of the eleven measurands. This assessment provided detailed information on the measurement quality and the measurement environment and application. Each technical discipline at each contractor site was solicited for their measurement needs. These inputs were evaluated and summarized into specifications of required measurement capability. Figures 13 and 14 illustrate the breadth of responses and type of detailed data contained in the consortium requirements. The consortium effort provided much detail regarding the specific measurement requirements, yet it also lacked the advocacy from the technical disciplines to program management that was experienced during Tech Mat.

The second task in the consortium program was to assess the most promising measurement techniques for each measurement need. Where the technology was deficient, a technical approach and development program were recommended. Figure 15 summarizes the recommendations from this task. With the exception of control position sensing, all of the measurement areas required substantial development. Unfortunately, at this point the consortium was terminated because of lack of funding and the end of competition in the NASP program.

There have been no subsequent refinements to the measurement requirements. These requirements led to several development efforts which will be discussed in the following section.

Instrumentation Development Status and Accomplishments

After the instrumentation consortium, the NASP program supported instrumentation development through contractor work packages, government work packages, the Small Business Innovative Research (SBIR) program, and the NASP Test Directorate. This work took place through a centralized instrumentation effort as well as through the disciplines.

In the centralized instrumentation program, the contractor and government efforts were structured to be complementary in addressing the measurement problems. Unfortunately, funding limitations had adverse impacts on the scope and the depth of the development activities. There has been a progressive reduction in the scope of the development work from 11 measurement areas to 8. Figure 16 shows this decrease in scope from the initial work to the present. In addition, the funding was so severely limited that for a given measurement area only a small portion of the actual measurement deficiency could be addressed. For example, in the case of heat flux (Fig. 8), the issues of transducer compatibility, installation technique, measurement fidelity, and data analysis method must be addressed for each of these seven measurement applications. However, with the existing funding only two measurement techniques are being investigated for one material-structural system. Clearly, this increases technical risk to the program.

Limited additional development has been supported by the technical disciplines. This includes work to apply nonintrusive flow measurement techniques to NASP tests, investigation of nondestructive evaluation techniques, and development of skin friction measurement techniques for extreme environments.

Development Progress

Despite the limited funding, some important progress has been made in addressing NASP measurement deficiencies. The following table summarizes the work accomplished during the current phase, and is organized by parameter development area.

Further Work

Despite this progress, much development remains to be done. A particularly pressing need is in the area of off-surface, nonintrusive measurements. High-temperature strain measurement is another area in need of improved measurement capability. Proof-of-concept development must advance in parallel with other disciplinary technology to assure that meaningful testing can be accomplished.

Lessons Learned

This section highlights several important lessons garnered from the NASP program regarding the understanding of measurement requirements and the development of instrumentation.

- Instrumentation must be treated as a discipline for technology development programs organized on a disciplinary basis.

For many technical disciplines, making measurements is considered an adjunct to the normal technical task. Many experimenters design instrumentation systems to support their own testing and usually rely on off-the-shelf hardware to accomplish the measurement requirements. When conducting parallel technology development in extreme environmental conditions, the measurement needs often exceed the capability of off-the-shelf equipment. Acquiring reliable test information from an extreme environment requires design and engineering from a measurement perspective not unlike that needed for technology advancement in a nonmeasurement discipline. The same challenges exist with regard to thermal, chemical, electrical and mechanical environments to which is added the need to minimize disturbances to the measured parameters. In this environment, the only way that instrumentation can receive appropriate emphasis, visibility, and resources is for it to be recognized as the unique discipline that it truly is.

- Measurement technology development must proceed in parallel with other disciplinary development to assure testability of technology test articles.

When validating the performance of test articles, the lack of critical measurement capability can preclude the ability to conduct meaningful tests. In spite of the soft requirements definition, it is possible to identify and mature measurement concepts early on and wait for specific measurement applications to be done when the design is mature. Running fast is good, but starting early is better.

- Sensitivity and uncertainty analyses are required to validate requirements.

Program requirements must be validated using critical sensitivity and uncertainty analyses. Otherwise valuable resources may be expended in the development of measurement capability that does not address real program needs.

Concluding Remarks

Instrumentation technology must be advanced on a broad front to meet the demanding requirements of the National Aero-Space Plane program. Further development work is needed to measure performance of critical propulsion and structural systems to the accuracy required for successful development of an airbreathing single-stage-to-orbit vehicle. Important breakthroughs have been achieved in many disciplinary areas, however, similar advances have not occurred in instrumentation technology. All research programs begin and end with data, and the quality of the data is constrained by the state of the art in measurement and instrumentation technology.

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Table

Development areas	Objectives	Accomplishments
Strain	Develop PdCr and FeCrAl resistance gauges for operation to 1500 °F and characterize behavior on NASA materials.	Successful compensation of FeCrAl and PdCr gauges has reduced apparent strain by an order of magnitude.
	Develop fiber optics measurement approaches using sapphire fibers.	Work just initiated.
Temperature	Characterize performance of fiber optic distributed temperature measurement system at 1000 °F.	Identified and solved optical fiber/measurement system compatibility problems.
	Develop techniques for attaching optical fibers to NASP materials and structures.	Identified preferred techniques for attaching optical fibers to TMC and superalloy materials.
	Demonstrate techniques for fiber optic temperature measurement at 2000 °F.	Work terminated.
Heat flux	Develop fiber optic dual temperature measurement approach for cooled panel structures.	Sensor fabricated and characterized. Installation techniques evaluated. Ready to install and test.
	Develop thin film differential thermopile and apply to NASP material.	Prototype devices calibrated and tested on ceramics and metals. Starting trials on NASP materials.
	Develop and evaluate 2-D inverse thermal analysis tools for application to NASP structures and materials.	Code used to analyze sensor installation approaches for cooled panels. Performance of embedded T/C approach quantified.
	Validate parameter estimation codes for determining thermal properties of NASP materials.	Work just initiated.
Pressure/ microphone	Develop 2000 °F fiber optic microphone with frequency response up to 100kHz and dynamic range of 130–190 dB.	1000 °F sensors fabricated and in test. 2000 °F sensor fabricated, testing to begin soon.
	Develop a pneumatic line analysis and compensation tool for analyzing small diameter pressure lines with high-temperature gradients.	Model evaluated using low-temperature data shows good agreement. High-temperature test facility under development.
Gas diagnostic system development	Develop multicomponent nonintrusive measurement system for application to high-enthalpy combustor testing in impulse facilities. – planar LIF of OH – double pulse and double plate holographic interferometry – high-speed schlieren	System fabricated and tested in Cal Tech T-5 facility as part of high-speed combustor test. System undergoing modification to upgrade PLIF cameras, improve ability to quantify OH, and improve schlieren camera.

Table Concluded.

Development areas	Objectives	Accomplishments
Gas diagnostic system development	Apply diagnostics to NASP combustor tests. – OH PLIF – O2 PLIF – O2 LOS absorption Apply diagnostics to NASP aerodynamic tests. – Raman in Mach 6 tunnel – Rayleigh in Mach 6 tunnel	Successful measurements within shock layer of NASP model.
Resonant holography	Develop resonant holographic interferometry for OH including laser source and recording techniques.	Feasibility demonstrated in lab with CW tunable lasers. Evaluation of pulsed laser source underway.
High-temp optical fiber	Develop low attenuation 2000 °F silica fiber. Develop low-loss sapphire fiber for use in microphone and temperature sensing. Develop low-loss sapphire silica splice.	Ni/Cr/Pt coated silica fiber fabricated and tested-identified problem with coating integrity. Modifying coating process. Low-loss sapphire (2, –4, dB/m) fabricated using laser heated pedestal growth. Low-loss splice (1.4 dB) fabricated using aluminosilicate glass jumper.
Skin	Develop sensors for operation in high heat flux combustor tests.	Floating element sensors fabricated and tested in Mach 2 and 3 combustor flows with heat fluxes to 400 BTU/ft^2-sec.
Nondestruct methods	Develop and evaluate advanced NDE techniques for analyzing NASP materials and structures.	Thermal diffusivity, magneto-optical imaging and shearography techniques have been evaluated for NASP materials and structures.

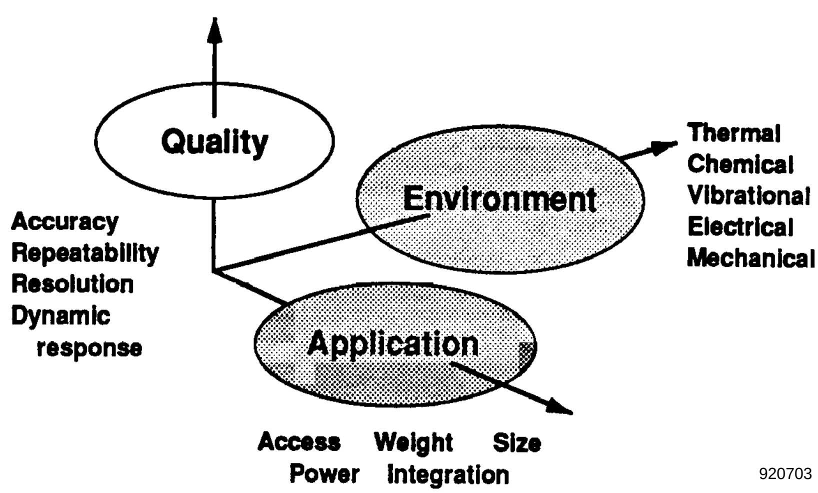

Fig. 1 Dimensions of instrumentation requirements.

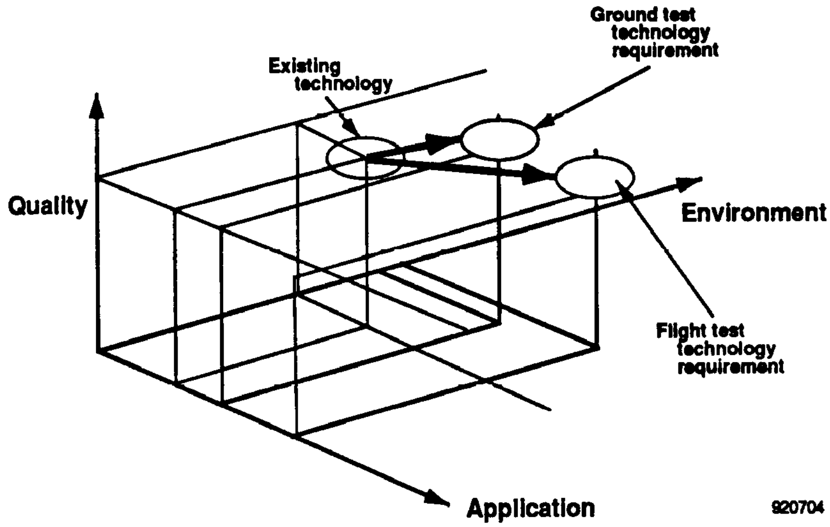

Fig. 2 Technology capability.

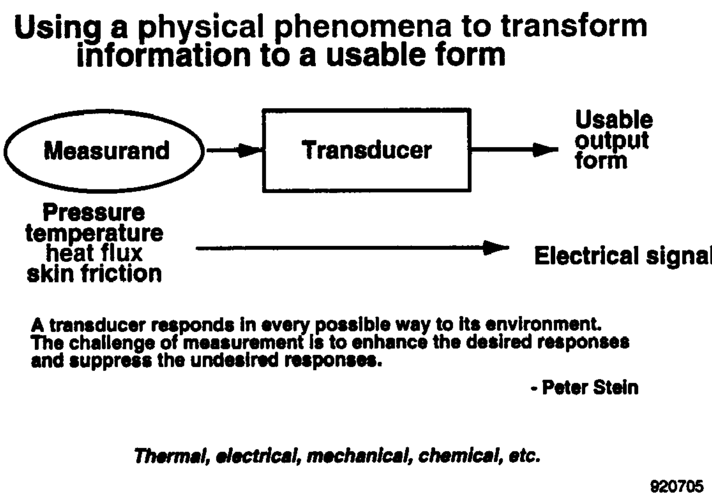

Fig. 3 Making a measurement.

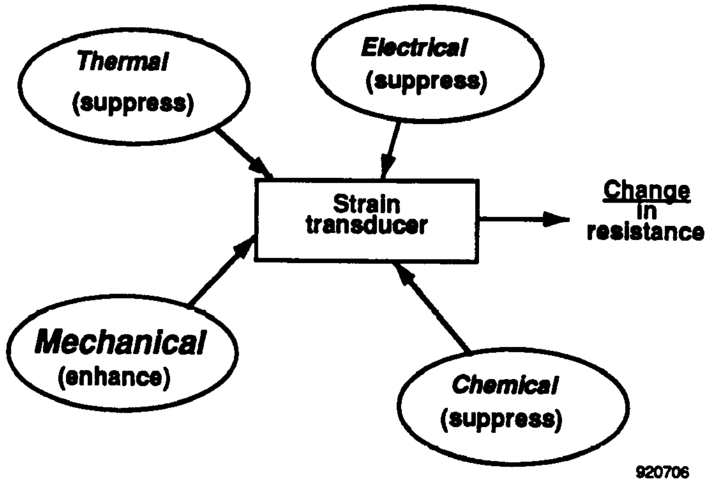

Fig. 4 Strain transducer responses.

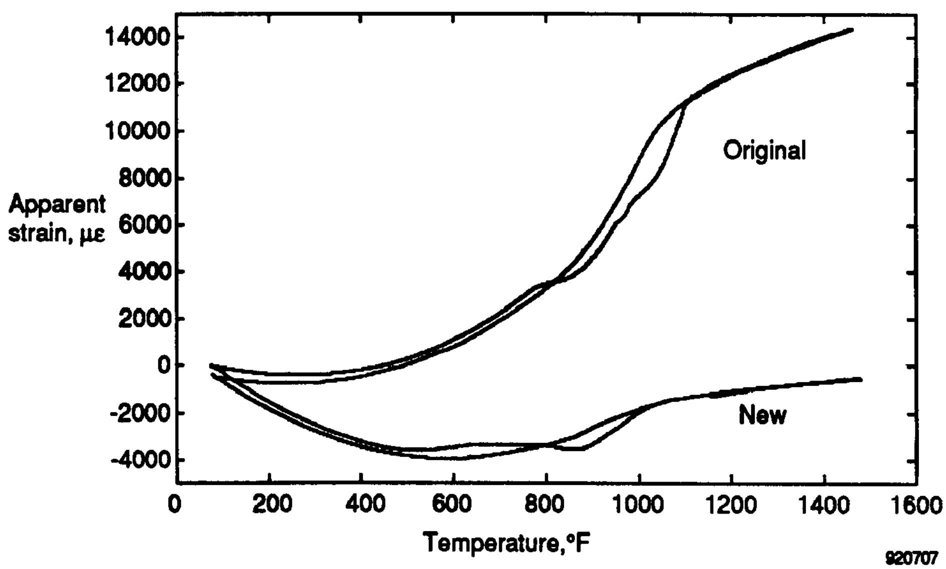

Fig. 5 Temperature effects on strain gauge performance.

	X-15	Asset	Shuttle	NASP
Materials		X	X	X
Structural concepts	X	X		X
Thermal control concepts				X
Airframe concepts	X	X	X	X
Engine concepts				X
Flight control concepts	X	X	X	X
Subsystems			X	X
Instrumentation	X	X	X	X
Analytical tools	X	X	X	X
Testing	X	X	X	X

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Fig. 6 Parallel technology development.

Ground test sensors	Flight test sensors
Short life (1 hr)	Long life (100 hr)
Large, heavy	Small, light, low power
Allow complex	Desire simple
Broad funding base	Narrow funding base
Repairable/replaceable	Nonrepairable
High performance	Lower performance?
Can isolate effects	Must treat combined effects

Requirements are broad enough that one solution will not solve both problems

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Fig. 7 Typical ground v. flight requirements.

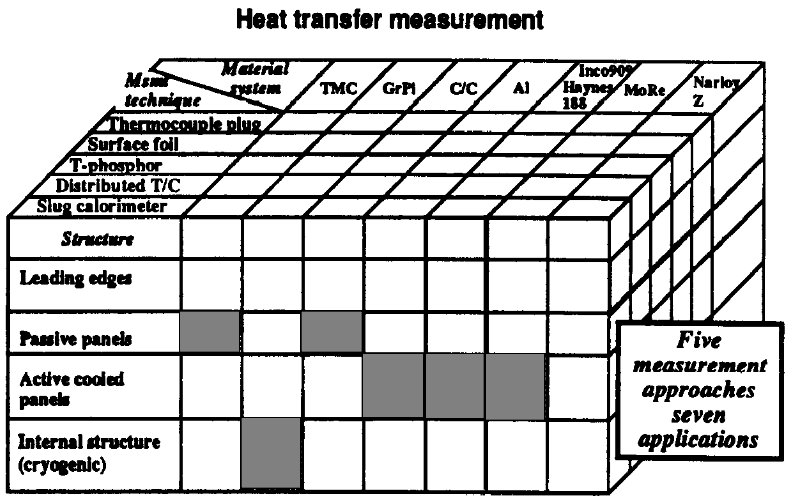

Fig. 8 Scope of the typical measurement problem.

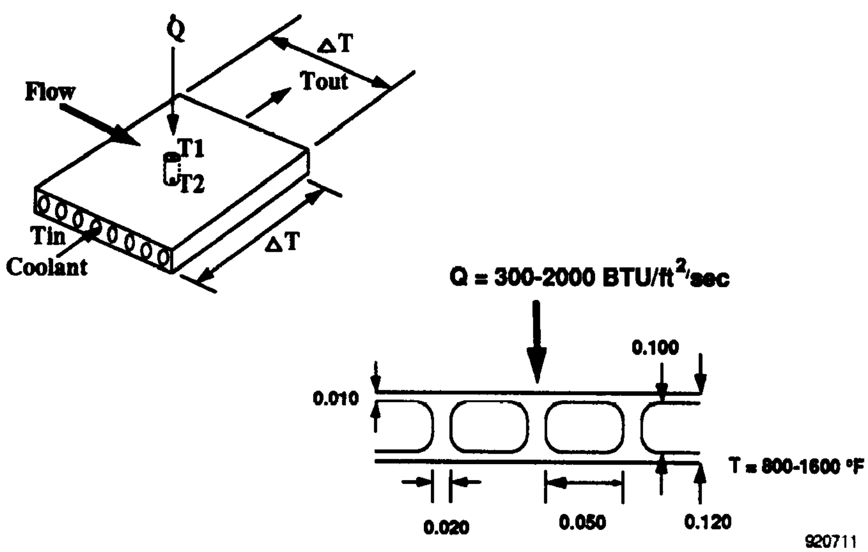

Fig. 9 Typical actively cooled panel configurations.

Location	Temperature, °F	Heat flux, BTU/ft2-sec	dT/dt, F/sec	Acoustic, dB	Vibration, g
Actively cooled panels					
Engine	–200/1,800	2,000	1,000	200	500
Airframe	–200/1,200	300	1,000	190	350
Leading edges					
Engine	–200/2,000	10,000/50,000	1,000	190	200
Airframe	–200/1,200	2,000	1,000	170	350
Passively cooled panels					
Carbon/carbon	1,800/3,000	60	250	190	300
Metal matrix composite	0/1,800	15	100	180	300
Cryogenic tankage	–430/150	1	500	150	30

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Fig. 10 Extreme measurement environments.

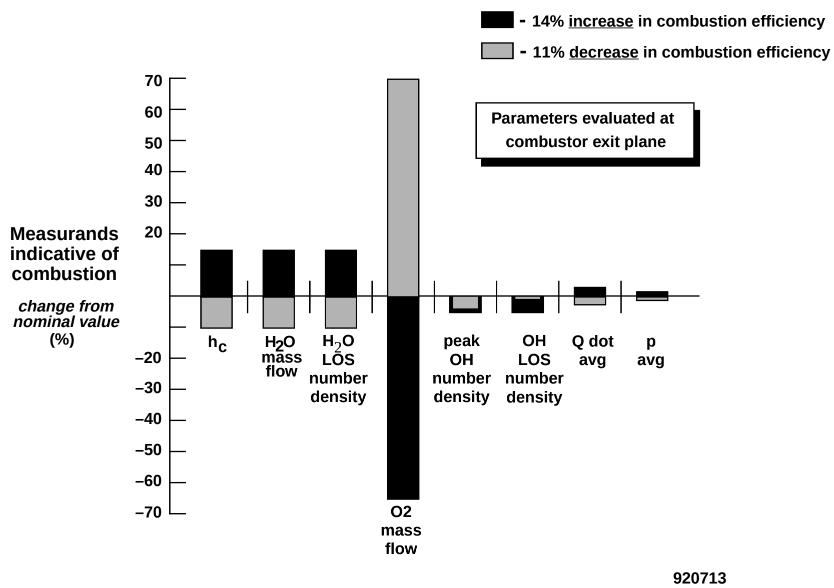

Fig. 11 Combustor parameter sensitivity.

Measurands

Airdata
Altitude
Catalycity
Deflection
Density profile
Flow velocity
Slush hydrogen
Heat flux
Control position
Pressure
  Surface
  Free stream
Shock position
  Species profile
Strain
Structural integrity

Measurands (cont.)

Temperature
  Surface (skin)
  Structural
  Flow
Transition/skin friction
Vibration

Technologies

Fluorescence flow measurement
Material properties
Nondestructive evaluation
Optical sensors
Measurement standards
High-temperature wiring

Recommended investment $33.6 M

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Fig. 12 Instrumentation task force measurement priorities.

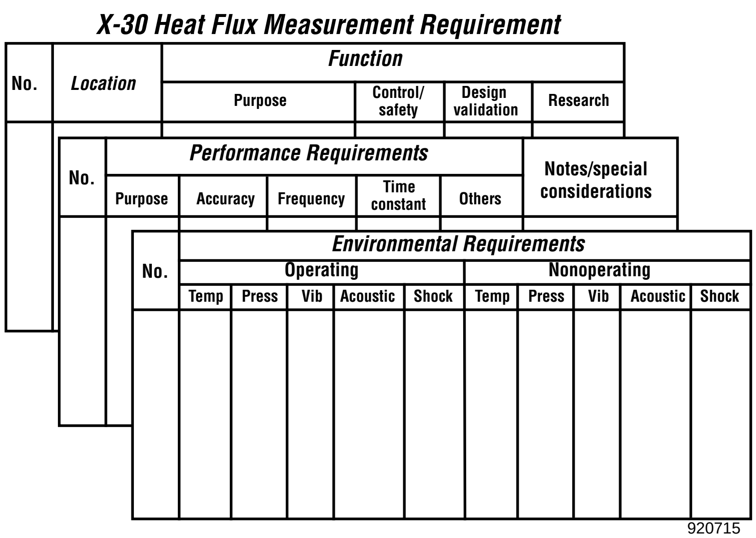

Fig. 13 Application requirement detail for NASP heat flux measurement.

X-30 Heat Flux Measurement Requirements

Location	Purpose	No of contractor requests					Total
		RI	MD	GD	RD	PW	
A/C areas LE	4,6,7,8	3	2	1		1	7
Inlet	4,6,10	1	2	1	1	1	6
Nozzle	4,7,8,9	1	1	1	1	1	5
Acreage							
C-C	6,7,8	3	1		1		5
Metal matrix	6,7,8	3	1		1		5
Control surfaces	7,8	2					2
Inlet ramp	6,7,8,9,10	2	2		1	1	6
Engine cowl	7,8,9	1	2		1		4
Nozzle	7,8,9,10	1	2		1	1	5
Chine							
Internal structure							
Wing box							
Landing gear							
Primary structure	7		1				1
Other							
Combustor	4,10		1			1	2
Cryo tanks	5		1				1
Cryo lines							
Misc engine							

Code	Purpose
4	Coolant control
5	Propelant boiloff & insulation
6	Validate CFD
7	Validate aeroheating methods
8	Define boundary layer transition
9	Obtain aerodynamic and plume heating
10	Engine performance

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Fig. 14 Application requirement detail for a NASP heat flux measurement.

Strain
- **Develop Pd-13 Cr foil gauge**
- **Prepare user guide for favorable available gauges**

Temperature & heat flux
- **Define concept for wide field optical hybrid IR/thermographic phosphor system (T&q)**
- **Demonstrate granted fiber optic distributed temperature sensor (T)**
- **Demonstrate dual phosphor typed fiber optic point sensor (T&q)**

Pressure
- **Develop high-frequency/high-temperature surface mounted fiber optic sensor**
- **Perform calculation to establish feasibility of standoff transducers**

Acceleration
- **Demonstrate fiber optic based accelerometer**

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Fig. 15 Consortium development recommendations for contractor activity in phase 2D.

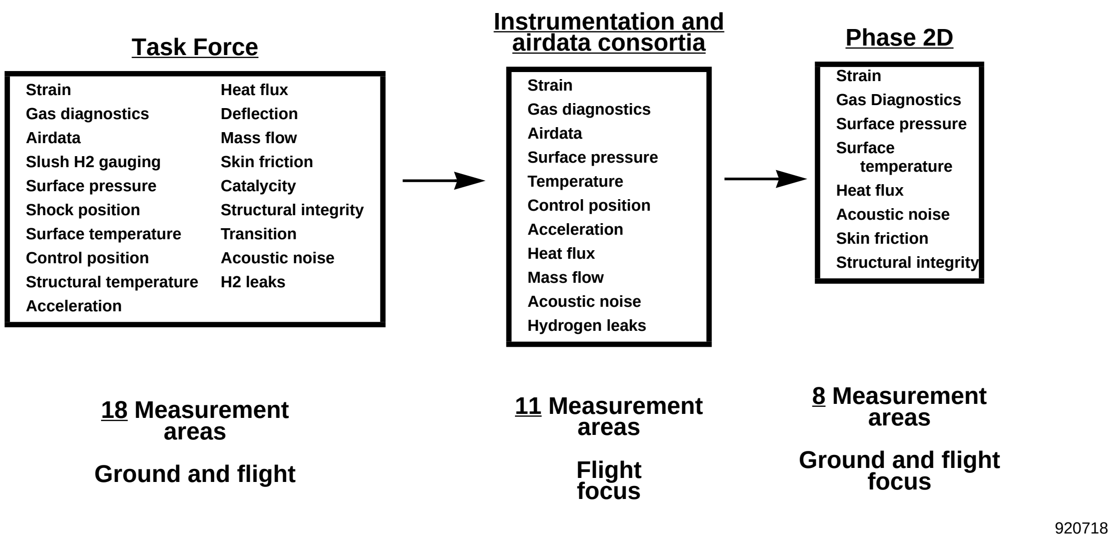

Fig. 16 Decreasing scope of NASP instrumentation development.

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Rodney K. Bogue and Peter Erbland

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NASA Dryden Flight Research Facility
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13. ABSTRACT (Maximum 200 words)

This paper presents a review of the requirement for, and development of, advanced measurement technology for the National Aero-Space Plane program. The objective is to discuss the technical need and the program commitment required to ensure that adequate and timely measurement capabilities are provided for ground and flight testing in the NASP program. The paper presents the scope of the measurement problem, describes the measurement process, examines how instrumentation technology development has been affected by NASP program evolution, discusses the national effort to define measurement requirements and assess the adequacy of current technology to support the NASP program and summarizes the measurement requirements. The unique features of the NASP program that complicate the understanding of requirements and the development of viable solutions are illustrated.

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