TECHNOLOGY – STRUCTURES AND THERMAL PROTECTION SYSTEMS

By

Roger A. Anderson
NASA Langley Research Center
Hampton, Virginia

Presented at the ELDO/NASA Space Transportation Systems Briefing
Bonn, Germany
July 7–8, 1970

INTRODUCTION

The approach taken in this presentation is to first develop a view of the space shuttle vehicles from the standpoint of the structural designer and discuss the major problems he sees. Secondly, the basic elements of a technology development program directed at solutions to these problems are identified, and selected elements of this program are illustrated and amplified with relevant technical data.

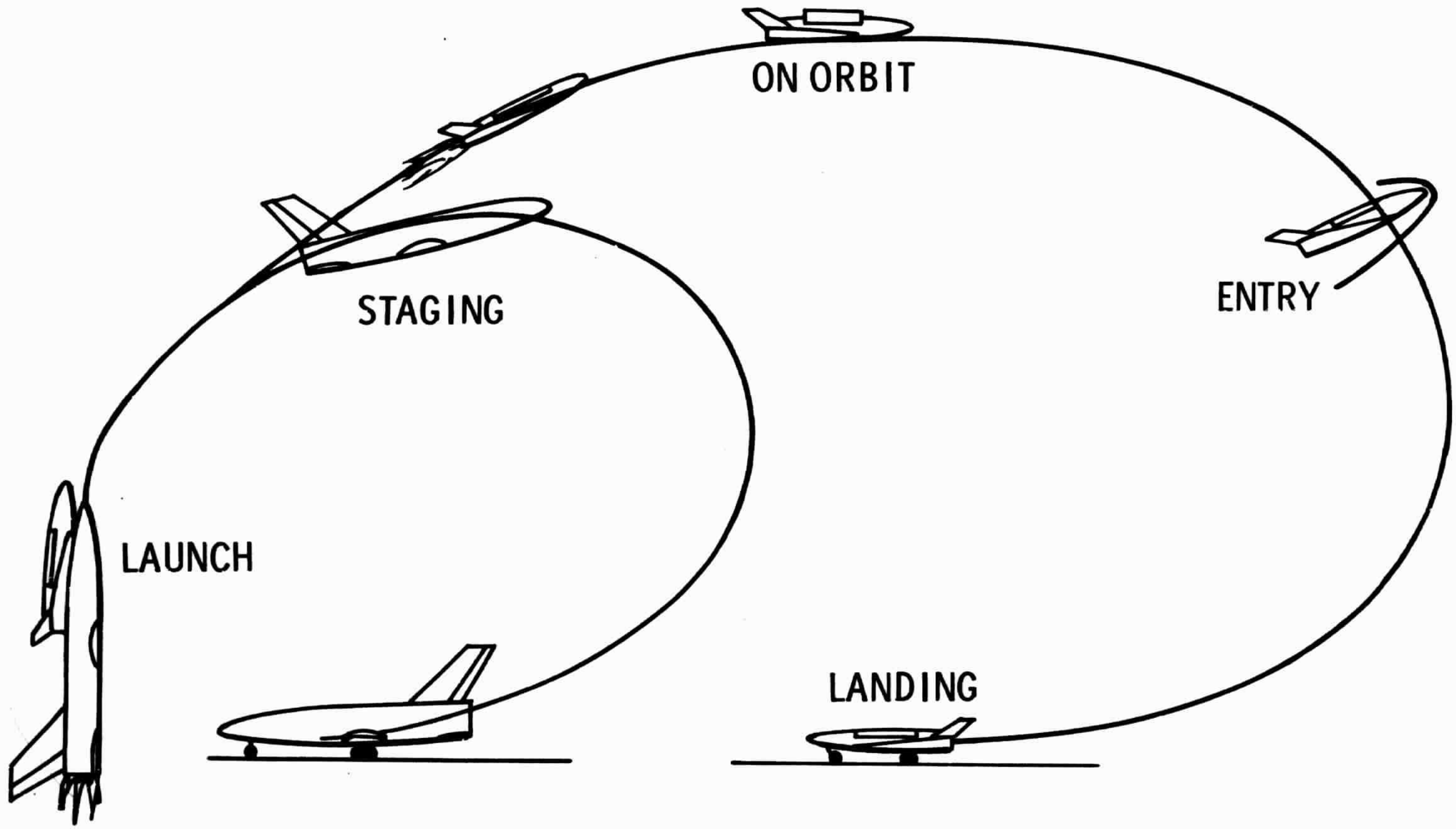
MISSION CHARACTERISTICS

(Slide 1)

The designer sees two very large aircraft-type vehicles which undergo a spectrum of aerodynamic, acoustic, and inertia loadings, and a severe aerodynamic heating environment during a portion of the return flight. When the above factors are coupled with a requirement for repetitive use with minimum-cost maintenance between flights, he understands that he is faced with a structural design challenge of unprecedented proportions.

He has had experience with each of the principal mission characteristics singly, or in simple combination, but with much smaller test vehicles. Drawing upon this background, he has proposed preliminary design solutions appropriate to the shuttle and its complex mission profile.

MISSION CHARACTERISTICS



- LARGE AIRCRAFT-TYPE VEHICLES
- SEVERE LOADS AND HEATING
- REUSE FOR 100 FLIGHTS

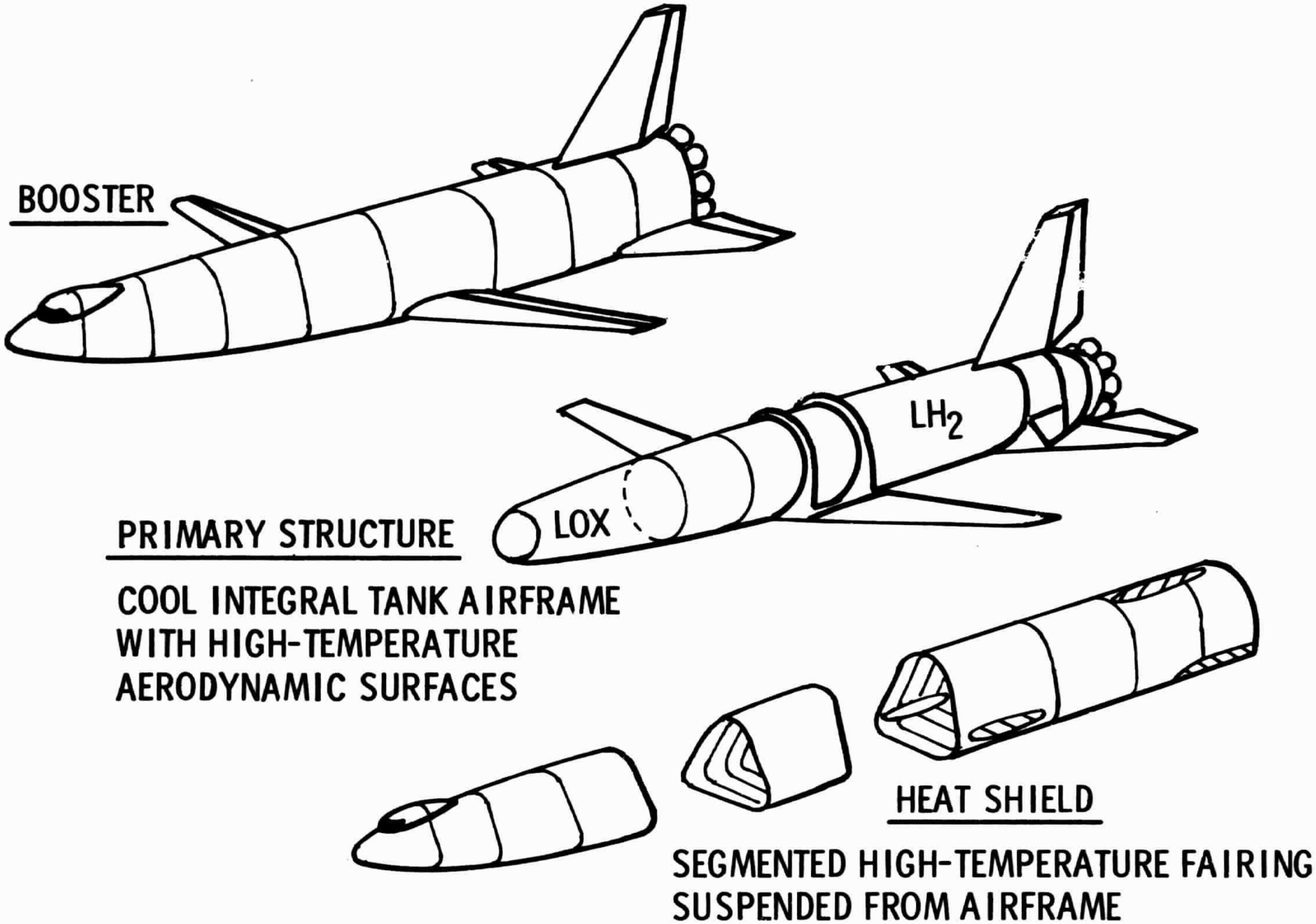
BOOSTER STRUCTURAL ARRANGEMENT

(Slide 2)

A rather straight-forward structural arrangement is currently visualized for the booster element of the shuttle as shown by the sketches. It consists basically of taking the familiar tank-airframe of conventional expendable boosters and fitting it with lifting surfaces for fly-back capability. Wing and tail structures may be designed as unprotected aerodynamically heated structures of nickel alloys with thermal expansion accommodation provisions at the attachment points to the cooler tankage.

The body or tankage areas are covered by a segmented high temperature metallic aerodynamic fairing which is suspended from the tankage-airframe. This fairing also serves as a heat shield designed to transmit the local aerodynamic pressure loadings to the tankage and not to participate in carrying primary axial thrust and bending loads. Readily available nickel alloys appear adequate for construction of this heat shield fairing with the exception of localized stagnation heating areas.

BOOSTER STRUCTURAL ARRANGEMENT



ORBITER STRUCTURAL ARRANGEMENTS

(Slide 3)

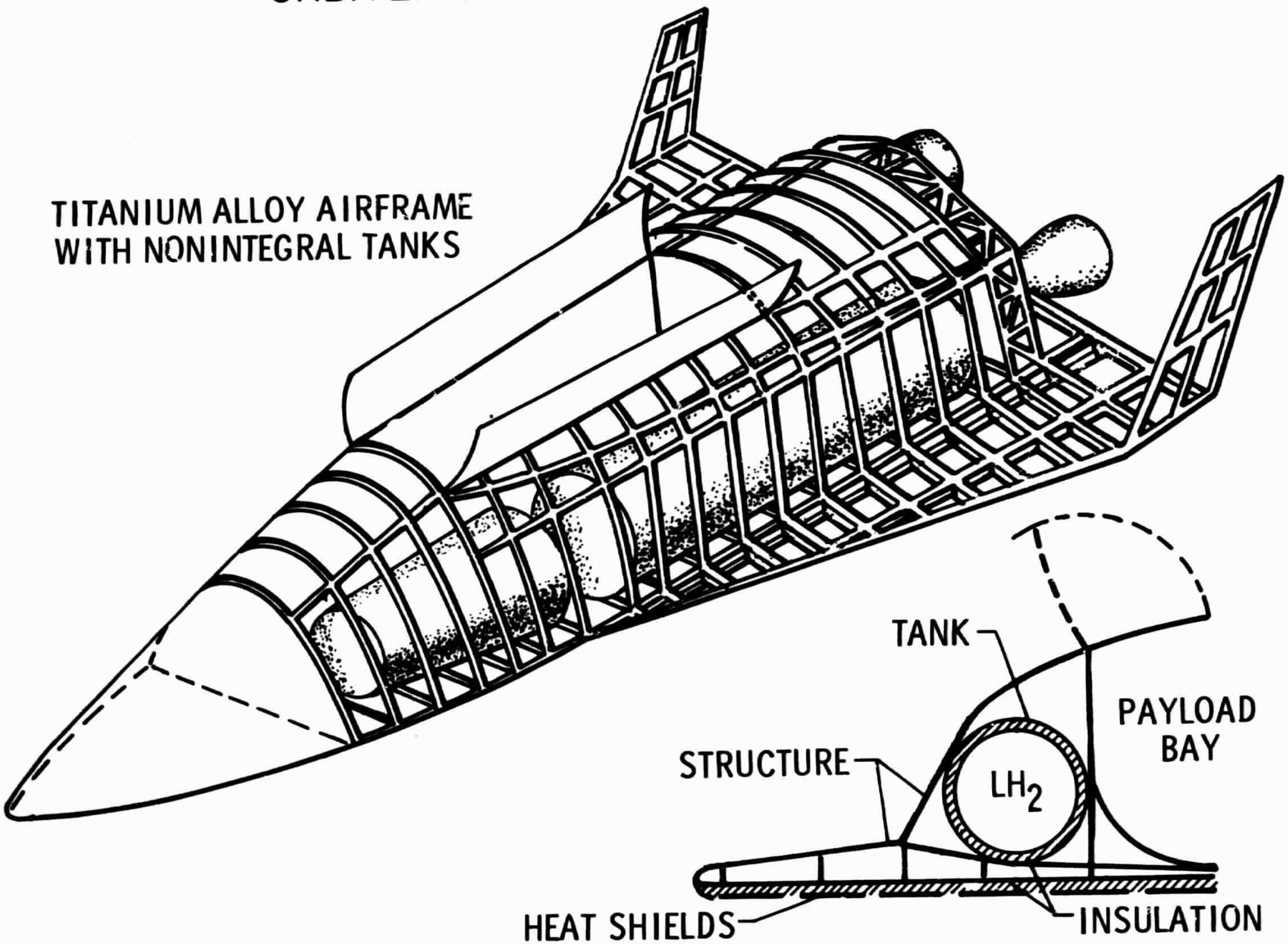
The orbiter is a more complex aerodynamic shape, dominated by the large cutout for the cargo bay. In contrast to the booster, the orbiter is generally visualized as a classic skin-stringer airframe sustaining both engine thrust and aerodynamic loads.

Propellant tanks are shown here as bodies of revolution suspended within the airframe and isolated from airframe strains in a manner which permits them to be designed primarily to carry propellant pressure and inertia loads. With cryogenic insulation on the inside of the tanks, the tank walls are somewhat thermally insulated from the cryogenic propellants.

The aerodynamic heat shields are shown closely conforming to the moldline of the vehicle. Dependent upon aerodynamic configuration and the alloy used for the airframe, heat shielding may or may not be needed on the upper surface areas. The sizes and details of the heat shield panels used on the orbiter are likely to differ substantially from those on the booster because of the more severe environment.

Overall, the orbiter is more weight sensitive and a more complex design problem than the booster with a number of structural options requiring investigation before an optimal system design can be decided.

ORBITER STRUCTURAL ARRANGEMENT



STRUCTURE/TPS DESIGN OPTIONS

(Slide 4)

The maximum temperature which should be allowed for the orbiter airframe is closely tied to decisions on construction and integration of the propellant tankage. Non-circular tankage permits better internal volume utilization and a somewhat smaller vehicle. Tankage integrated with the structure to the extent that it serves as the primary load paths may lead to further reduction of weight but a substantially more complex design problem.

Several non-conventional stiffened panel arrangements which offer weight saving need investigation in light of the fact that the external surface of the structure does not need to be smooth. (Non-aerodynamic surface.) Much work is going forward to understand the behavior of unconventional stiffened panels utilizing both metallic and filamentary composite materials. The potential weight savings using composite filamentary materials in selected structural components of the shuttle are judged to be highly significant and will be dealt with on later slides.

There are numerous metallic and non-metallic heat shield options to be considered including the use of active cooling systems for the stagnation areas of the vehicles. Because of minimal flight experience with heat shields, the basic consideration with the heat shield options is reliability and maintenance problems rather than solely weight.

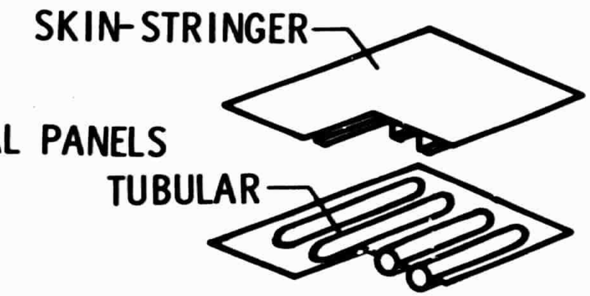
STRUCTURE / TPS DESIGN OPTIONS

OPTIMUM AIRFRAME TEMPERATURE

CIRCULAR VERSUS NONCIRCULAR TANKS

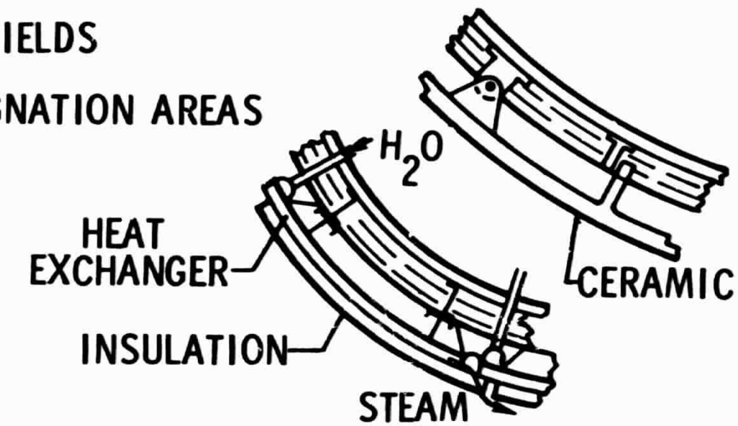
CONVENTIONAL VERSUS ADVANCED STRUCTURAL PANELS

USE OF COMPOSITE FILAMENTARY MATERIALS



METALLIC VERSUS NONMETALLIC HEAT SHIELDS

PASSIVE VERSUS ACTIVELY COOLED STAGNATION AREAS



DESIGN UNCERTAINTIES

(Slide 5)

The basic complexity of the structural system for the shuttle and the current lack of detailed load definition for the many phases of the mission leads to several major design uncertainties, which are summarized here.

Prior to detail design efforts, the accuracy of weight determination is always open to question. For the shuttle, this presents a major uncertainty because of the sensitivity of gross lift-off weight and particularly payload to changes in the dry weight of the orbiter. The slope of these curves is approximately 5 times steeper than those for high performance aircraft.

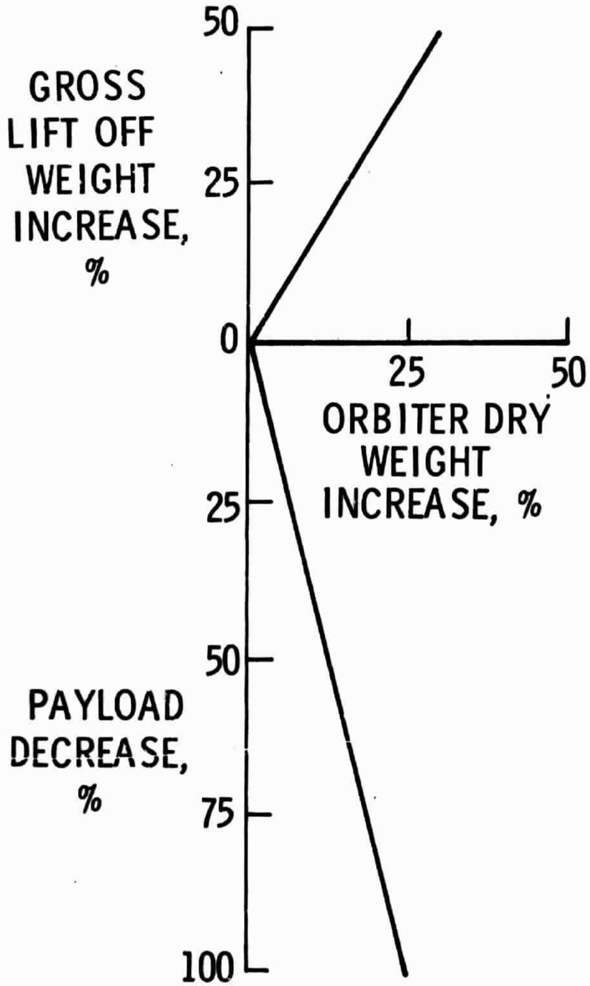
There is substantial uncertainty over the ability of several promising candidate materials for the thermal protection systems to withstand the operating environment for 100 missions. Available data suggests a more limited life with maintenance and repair at appropriate but as yet unknown intervals.

The sequence of tests necessary to establish initial flightworthiness of the structure and the maintenance and recertification procedures during mission operations are as yet undefined. Associated cost of these procedures will be determined by the quality of the initial design.

A major question is – what impact will application of advanced technology have on the system weight, reliability, and cost of the shuttle? The assumption is that a technology development program will produce timely and highly beneficial results.

In view of the aforementioned major uncertainties which arise when shuttle structural design is attempted with current technology, a selective technology development program has been initiated.

DESIGN UNCERTAINTIES



ACCURACY OF WEIGHT DETERMINATION

MATERIAL PERFORMANCE FOR 100 MISSIONS

PROOF TEST & RECERTIFICATION PROCECURES

IMPACT OF ADVANCED TECHNOLOGY ON SYSTEM WEIGHT, RELIABILITY, AND COST

BASIC ELEMENTS OF TECHNOLOGY PROGRAM

(Slide 6)

The program content has been developed with inputs from many sources and has been initiated as an interrelated effort in both government and industrial laboratories. Technical highlights of five of these activities will be dealt with sequentially on subsequent slides and brief explanatory comments follow on the remaining two program elements.

The structural design criteria development effort has produced a document for use during Phase B design studies. Additionally, several problem areas such as definition of repeated load spectra and definition of minimum requirements for full scale qualification tests have been identified for further in-depth study.

Materials and fabrication process development is primarily concentrated on the areas of cryogenic insulation, high temperature metals, filamentary composite materials, bearings, lubricants, and seals, and non-destructive inspection and repair techniques. In each area a technical goal has been established for accomplishment in a 2-3 year R&D effort.

BASIC ELEMENTS OF TECHNOLOGY PROGRAM

MISSION SIMULATION TESTING

CONSTRUCTION OF STRUCTURAL PROTOTYPES

STRUCTURAL DESIGN CRITERIA DEVELOPMENT

INTERRELATED EFFORT IN GOVERNMENT AND INDUSTRIAL LABORATORIES

ANALYTICAL METHODS DEVELOPMENT

THERMAL PROTECTION SYSTEM DEVELOPMENT

ADVANCED STRUCTURAL COMPONENT DEVELOPMENT

MATERIALS AND FABRICATION PROCESS DEVELOPMENT

METALLIC HEAT SHIELD DESIGN CONSIDERATIONS

(Slide 7)

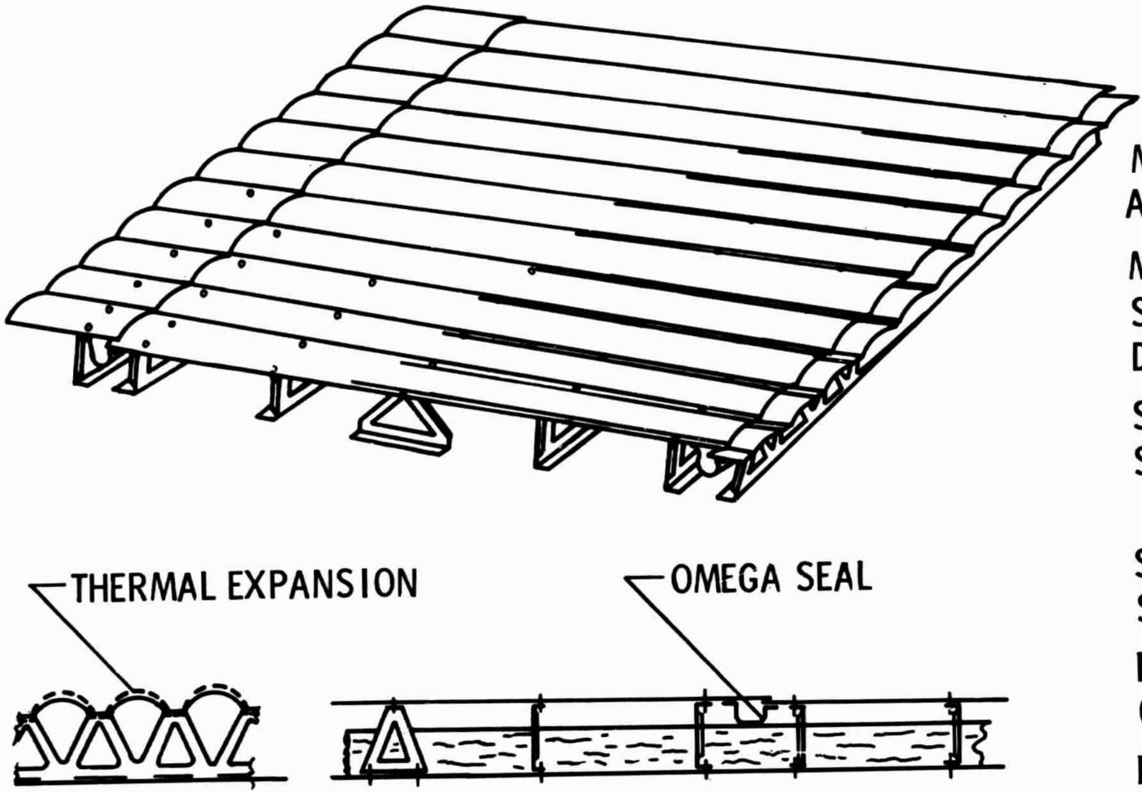
Substantial efforts have been expended over the past 12 years in the development of reliable light weight metallic panels which serve as the outer surface of the thermal insulation system for high speed vehicles. These efforts have been primarily concerned with the listed set of design problems common to metallic shields.

A needed extension of prior art is to increase the allowable dimensions between expansion joints to the order of a meter or more to minimize the number of parts on a vehicle as large as the shuttle orbiter. Illustrated here is one proposed design suitable for thin gage nickel alloys which accommodates thermal expansion in one direction by bending of the corrugated elements and by slip joints and rotation of the support elements in the other direction.

For those limited surface areas where coated refractory metals such as columbium must be used, current thinking is to employ integrally stiffened plates with generous corner and edge radii and overall dimensions of a half meter or less. Such designs are likely to be at least twice as heavy as a corrugated nickel alloy shield with this weight increase being dictated by reliability goals for ceramic coated refractory metal parts.

Some current results on oxidation resistance as well as on heating effects at gaps are presented on the next two slides.

METALLIC HEAT SHIELD DESIGN CONSIDERATIONS



MINIMUM WEIGHT AND LOW COST

MINIMAL THERMAL STRESS SHIELD DESIGNS

SHIELD JOINTS, SEALS, AND INTERNAL ACCESS

SHIELD SUPPORT SYSTEMS

INSULATION CONTAINMENT

ROUGHNESS DRAG AND LOCAL HEAT-ING

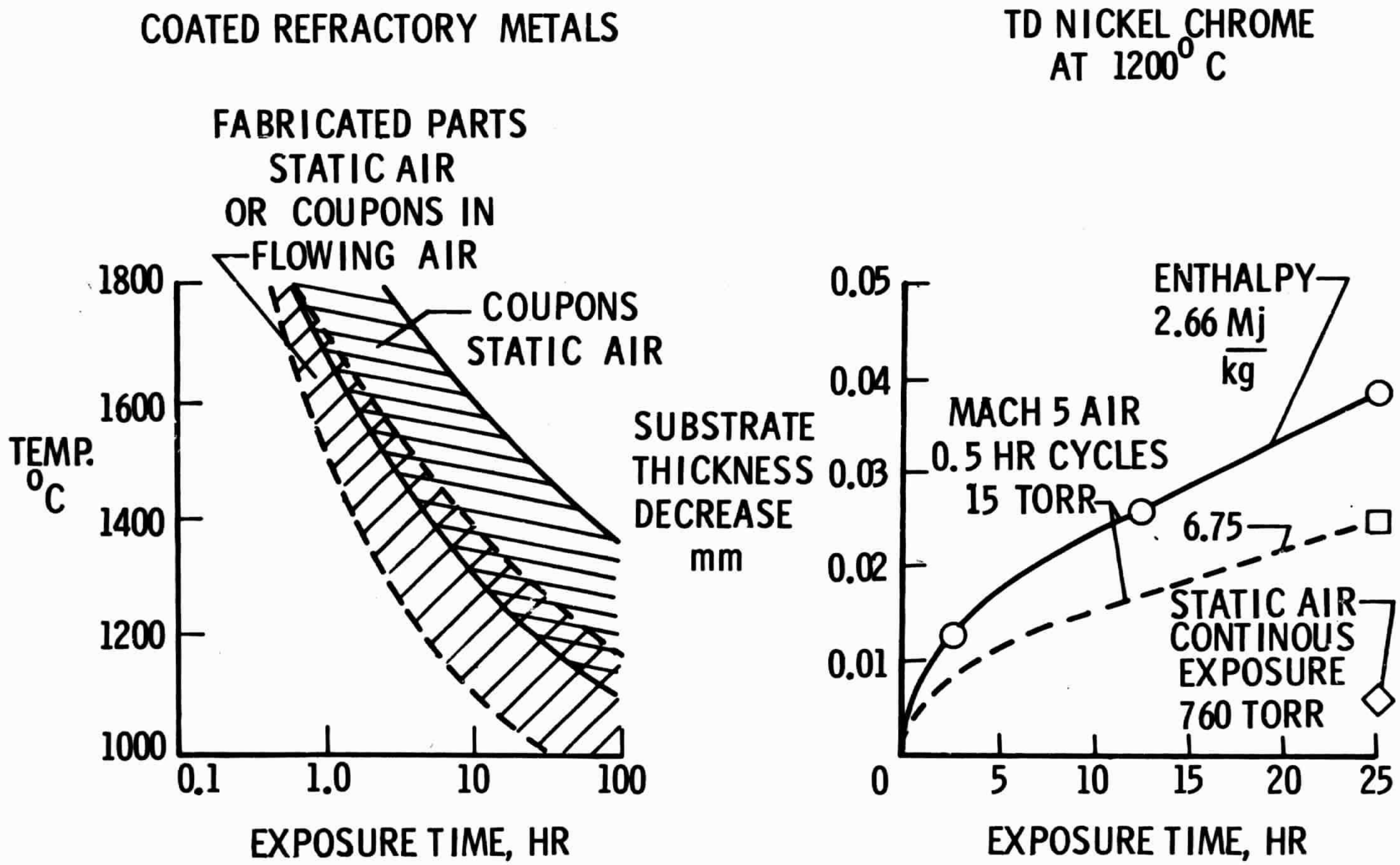
OXIDATION OF METALLIC SHIELDS

(Slide 8)

One of the major efforts of the technology program is to obtain data on the performance of coated refractory metals in simulated entry environments. The graph on the right shows that the behavior of material coupons in static air (oven) tests is substantially better than that of material coupons in flowing air tests or of fabricated parts in static air tests. In the temperature range of interest for application of refractory metal shields, 1100–1600° C, failure of fabricated parts is obtained in exposure times substantially less than that desired (25 hours) for shuttle design. While the failures are not catastrophic in the sense of jeopardizing completion of a flight, substantial effort is justified to eliminate the early random failures currently being experienced. This may be accomplished by further simplification of the design of parts and better process control during coating application.

An alternate material for heat shields at 1200° C and below are the dispersion strengthened nickel–chrome alloys which form stable oxides during environmental exposure. Available flowing air tests at increasing levels of stream enthalpy suggest that the demonstrated excellent performance in low pressure static air is achievable. Substantial effort is being placed on improving the quality of thin gage sheet material and on developing fabrication and joining procedures applicable to heat shield components.

OXIDATION OF METALLIC SHIELDS



TEMPERATURE AT GAP BETWEEN HEAT SHIELD PANELS

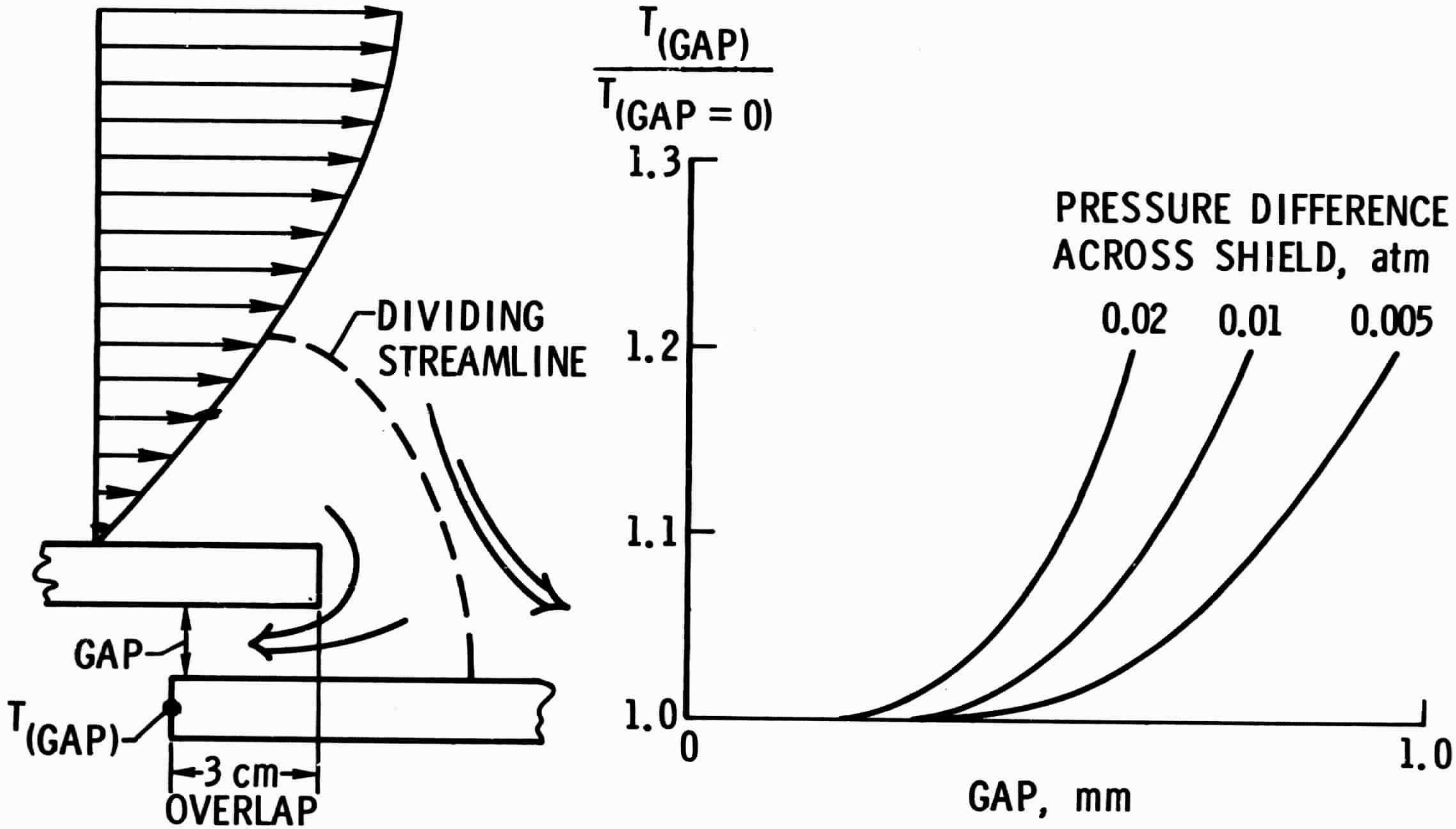
(Slide 9)

Substantial numbers of tests have been performed to understand the heating around proturbances and forward and rearward facing steps but little attention has been paid to air inflow heating due to a positive pressure difference across a gap. During reentry, hot boundary layer air can be expected to be drawn through the gaps that will exist between overlapped heat shields.

Calculations have been made, as shown by the graph, which indicate 10–20% temperature increases at the edges of metal shields which are shadowed by the overlap. In parts operating near their critical temperature limits on the non-overlapped areas, unexpected temperature increases of 100–150° C could seriously degrade the useful life of the parts. The degraded areas tend to be hidden from view during routine inspections.

A related problem for which little information exists is the internal heating due to movement of air which has entered through gaps on the windward surfaces of the vehicle. Control of this flow may require positive means for sealing gaps as shown on slide 7, or alternately the use of inert gas purge systems to provide positive outflow through gaps.

TEMPERATURE AT GAP BETWEEN HEAT SHIELD PANELS



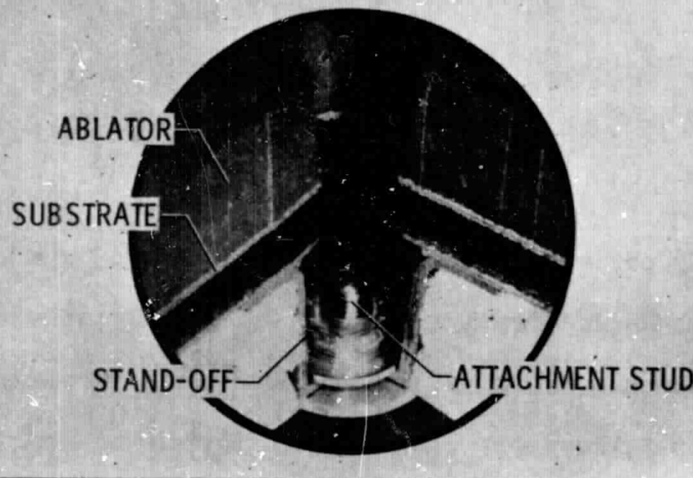
LOW-COST REPLACEABLE ABLATIVE HEAT SHIELD PANELS

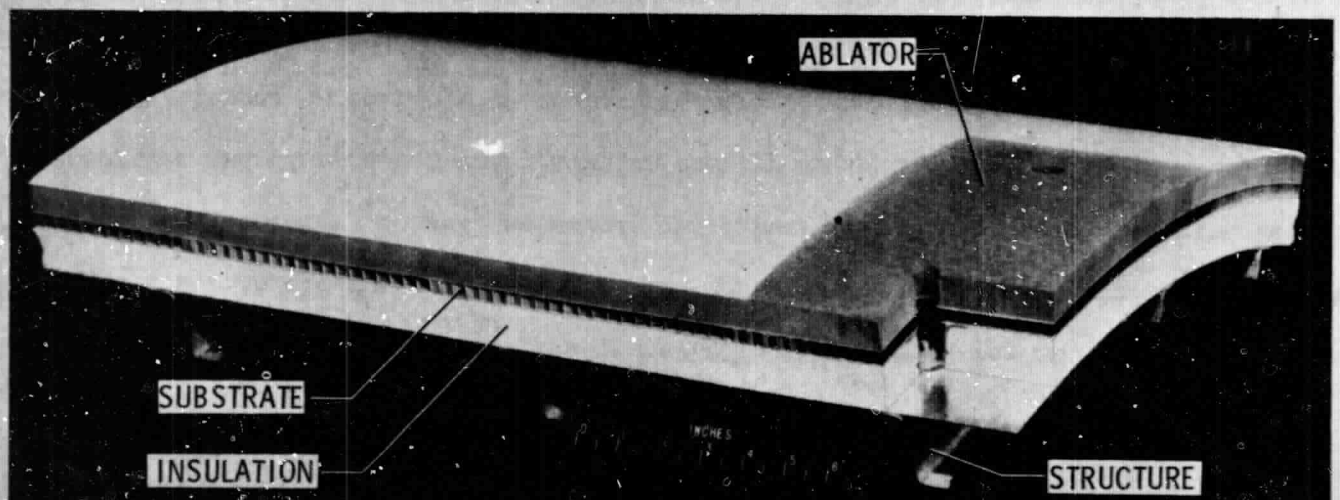
(Slide 10)

As a backup to metallic heat shield assemblies, a significant effort is being made to develop ablative shields which are low enough in cost to be replaced after each flight. Such shields could be used in the limited areas where maximum temperatures are above 1500° C where available non-ablative shield materials are currently exhibiting a limited reuse capability and are much more costly than ablative materials. Replaceable ablative shield panels, such as that illustrated, are undergoing further development to identify the types of manufacturing defects inherent in low cost fabrication procedures that can be tolerated in a space shuttle application.

A relatively recent heat shield concept receiving much attention is one in which refractory ceramic fibers are compacted with inorganic binders to form low density panels similar to the ablative panel illustrated – but capable of withstanding maximum temperatures approaching 1600° C without mass loss. Efforts are concentrated on improving the moisture and erosion resistance as well as the emissivity of these low density ceramic fiber materials by application of suitable surface coatings.

REPLACEABLE ABLATIVE HEAT-SHIELD CONCEPT





L1-1500 TESTING

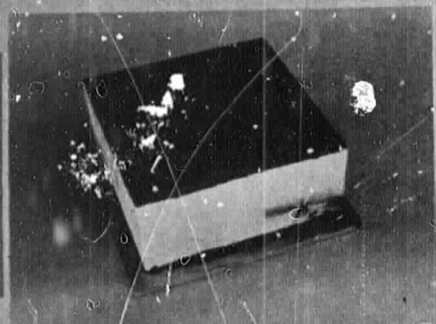
(Slides 11 and 12)

These slides illustrate some of the types of tests that have been run on a proprietary non-ablative compacted ceramic fiber shield known as L1-1500. The tests encompass several types of temperature exposure tests in the laboratory as well as mechanical property determination. Deficiencies in mechanical properties and dimensional changes which show up in cyclic heating tests are believed to be correctable through changes in composition and manufacturing procedures.

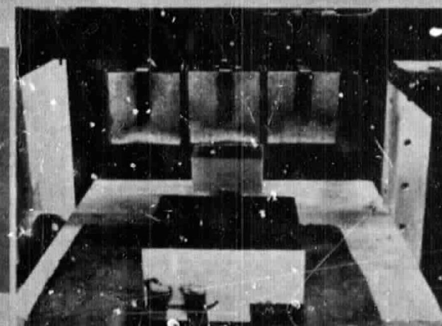
A small cylindrical sample has also been flown on a Pacemaker rocket which provided brief exposure to a high dynamic pressure heating environment. Low density ablative samples were tested on the same flight and all performed in an acceptable and predictable manner.

The thermal insulating capability of the current formulations appear to make the compacted fiber shield competetive in weight with the systems employing non-compacted fibrous insulations protected by metallic heat shields.

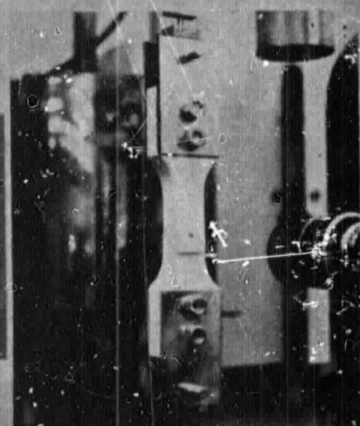
LI-1500 TESTING



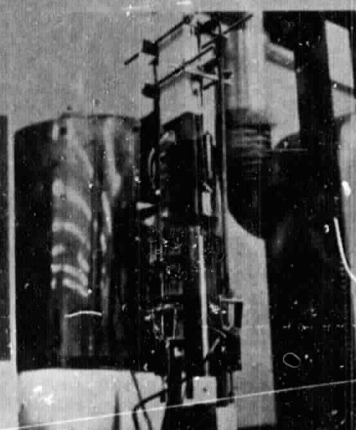
6 X 6 X 3 SPECIMEN



RADIANT HEAT

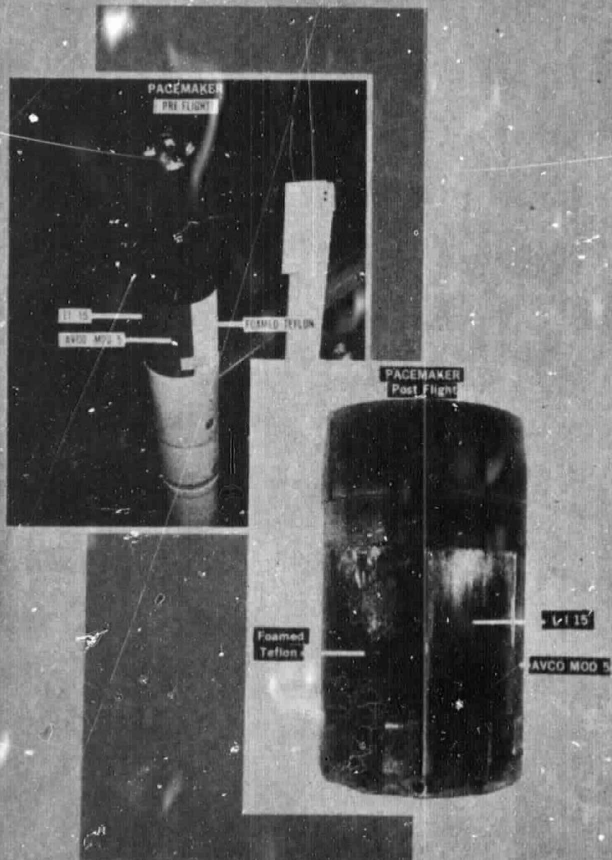


TENSILE TEST

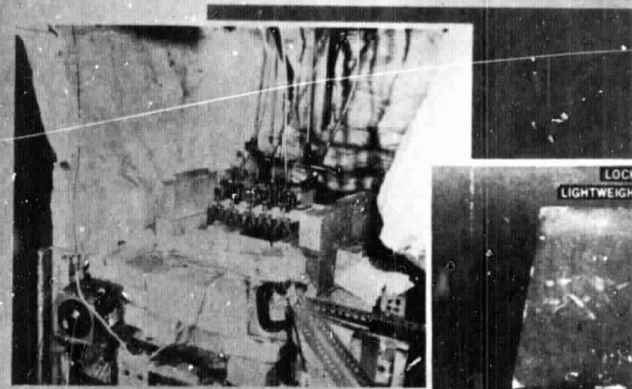


STRAIN COMPATIBILITY

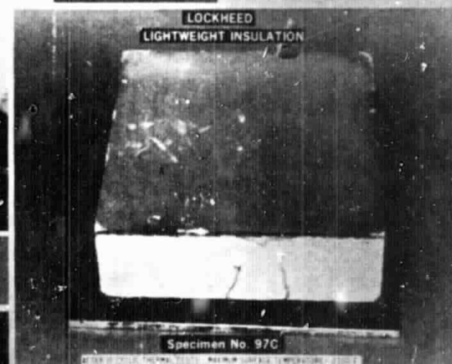
LI-1500 TESTING (CONT)



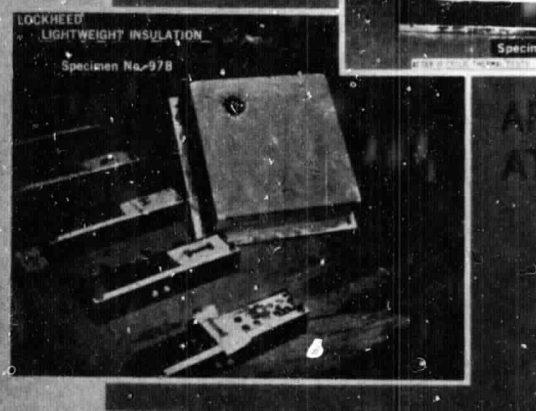
PACEMAKER



RADIANT HEAT FACILITY



AFTER 10 CYCLES AT 2300°F



AFTER 50 CYCLES AT 2500°F

FILAMENTARY COMPOSITE STRUCTURES

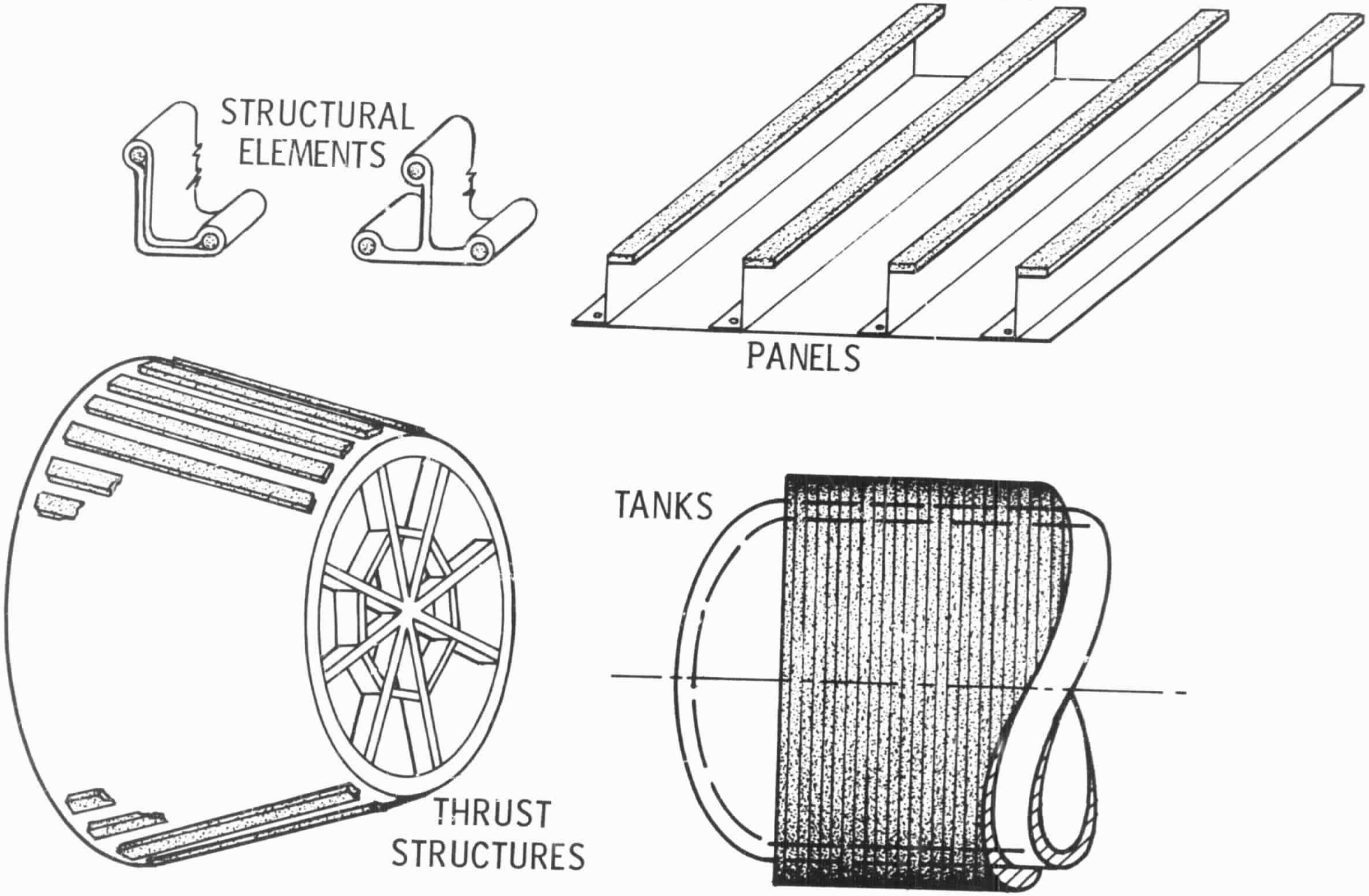
(Slide 13)

Illustrated here are some of the structural components for which weight reductions of the order of 20% are projected through application of advanced filamentary materials. Experimental work has been done on stiffener and ring elements, skin-stringer panels, and filament overwrapped tanks. Some of the parts of typical engine thrust structures are currently being designed for tests under simulated mission conditions.

In the applications shown in this figure, limited quantities of filaments are adhesively bonded to basically metallic structures in locations where the greatest enhancement of a desired structural property is obtained with a modest quantity of high cost filaments. We call this the selective reinforcement approach as opposed to the somewhat more familiar all filamentary composite structure which uses metal inserts only at critical locations such as at joints between major components.

A more detailed look at the performance and some of the problems with filament reinforced structures are shown on the following two slides.

FILAMENTARY COMPOSITE STRUCTURES
POTENTIAL 20 PERCENT WEIGHT REDUCTION



ALUMINUM TUBE REINFORCED WITH BORON/EPOXY

(Slide 14)

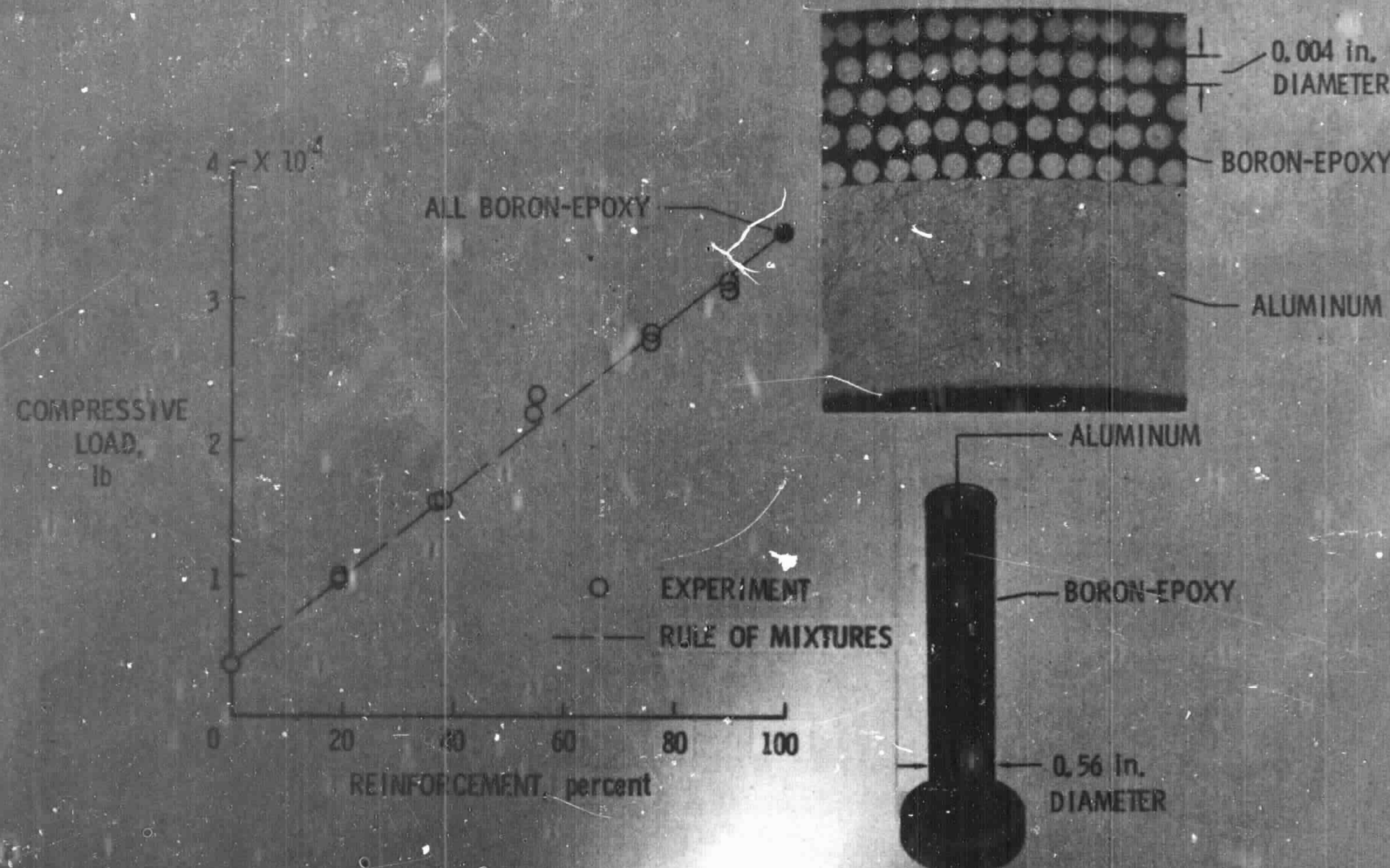
Early experiments on the reinforcement of metal structural parts with high stiffness filaments were conducted on aluminum tubing. As seen by the enlargement of a section of the tube wall, the filaments are all aligned in the axial or primary loading direction.

The graph compares the load carrying capacity of a series of short equal weight tubular specimens in which the tube cross section was varied from all aluminum to all boron–epoxy. The strength increased linearly according to the rule–of–mixtures. In tests in which Euler column buckling was the mode of failure, a highly favorable non–linear increase in load was obtained with boron–epoxy overlays on aluminum tubes. This non–linear behavior makes it possible to obtain significant weight reductions with small selective additions of high cost filamentary material to reinforce metal members.

To circumvent the problems of developing a whole new technology for joints between such composite material members, substantial work has been done in making transitions from several boron layers to an all metallic member at its ends. The performance of such members in both static and fatigue tests is currently under investigation.

ALUMINUM TUBE REINFORCED WITH BORON-EPOXY

CONSTANT TOTAL WEIGHT



FILAMENTARY COMPOSITE TESTS

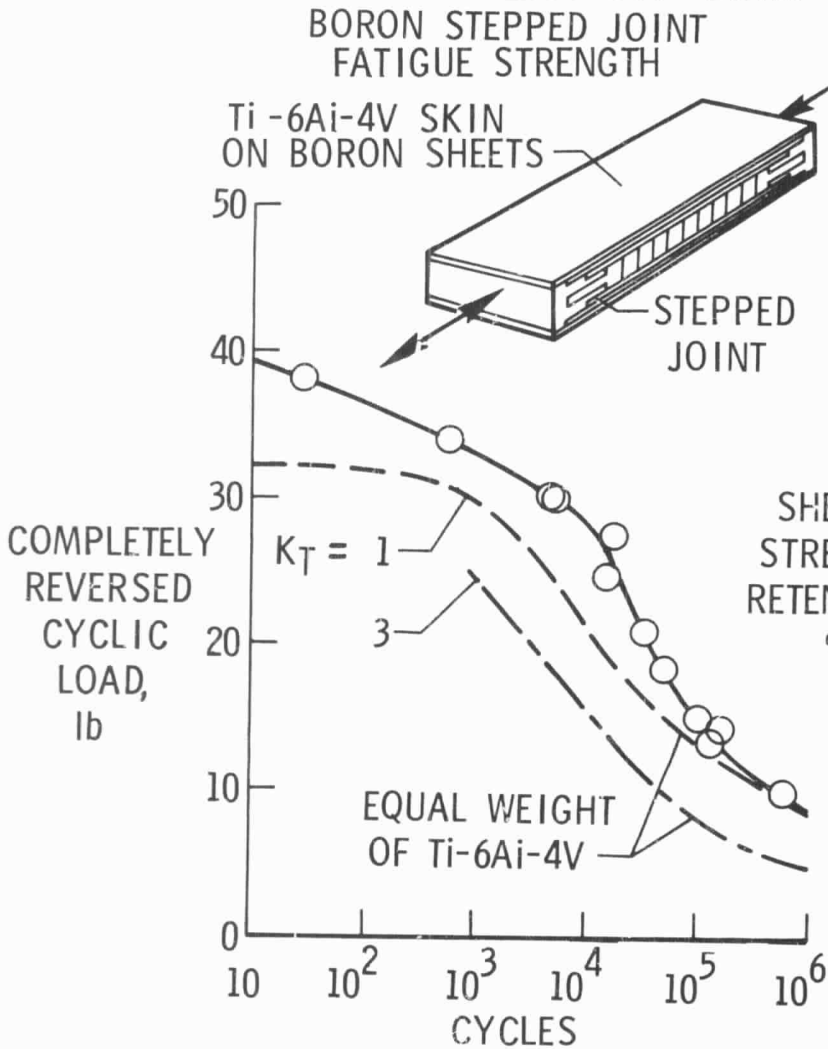
(Slide 15)

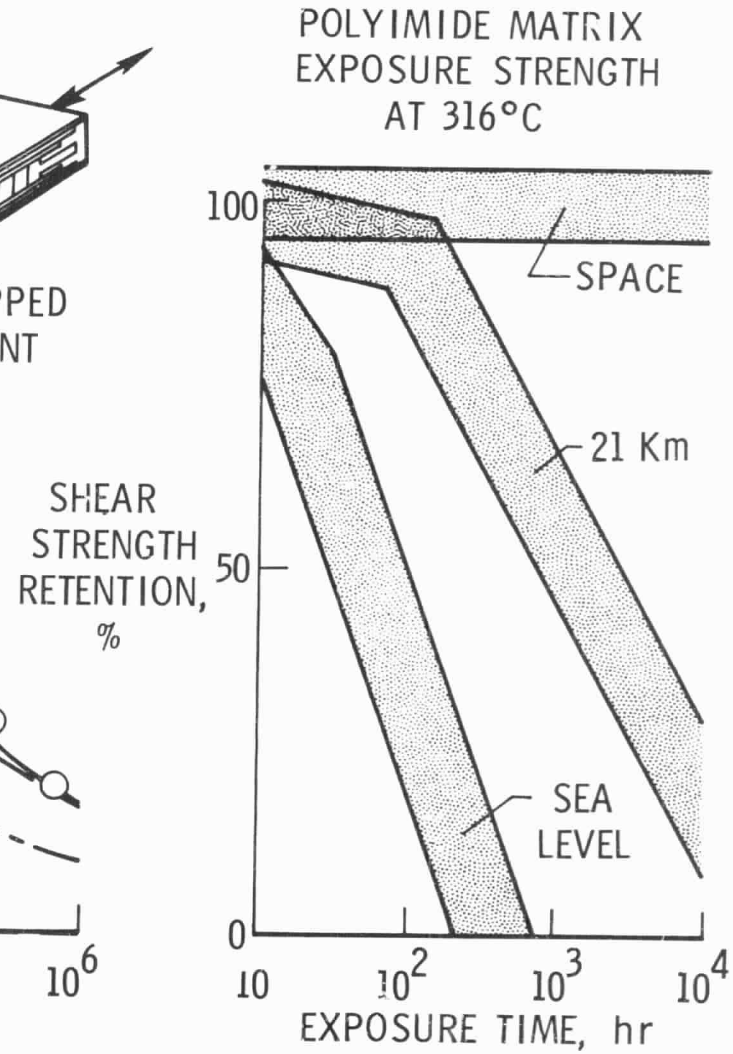
The graph on the left illustrates recently obtained fatigue results for a joint or edge treatment for a boron reinforced honeycomb sandwich panel. The transition from each boron layer to metal was accomplished through a series of steps. These specimens were subjected to completely reversed cyclic in-plane loads. Inspite of the complex nature of the construction, the test data indicate that the composite construction yields a fatigue life which compares favorably to both notched and unnotched titanium plates of equal weight.

The graph on the right illustrates the results of some of the efforts to develop a temperature resistant matrix material for filamentary composites. Experiments with polyimide resins at 316° C indicate that the shear strength retention of filamentary composites is strongly influenced by the exposure duration at various atmospheric pressures. From these results we infer that oxidation is the primary mechanism for degrading the performance of organic resin matrices.

Much additional work is required to define operational limits for filamentary composite construction with organic resin adhesives. Because of limitations in high temperature applications, consideration is being given to development of the metal matrice filamentary composite materials which are now emerging as construction materials.

FILAMENTARY COMPOSITE TESTS





FINITE ELEMENT REPRESENTATION OF STRUCTURE

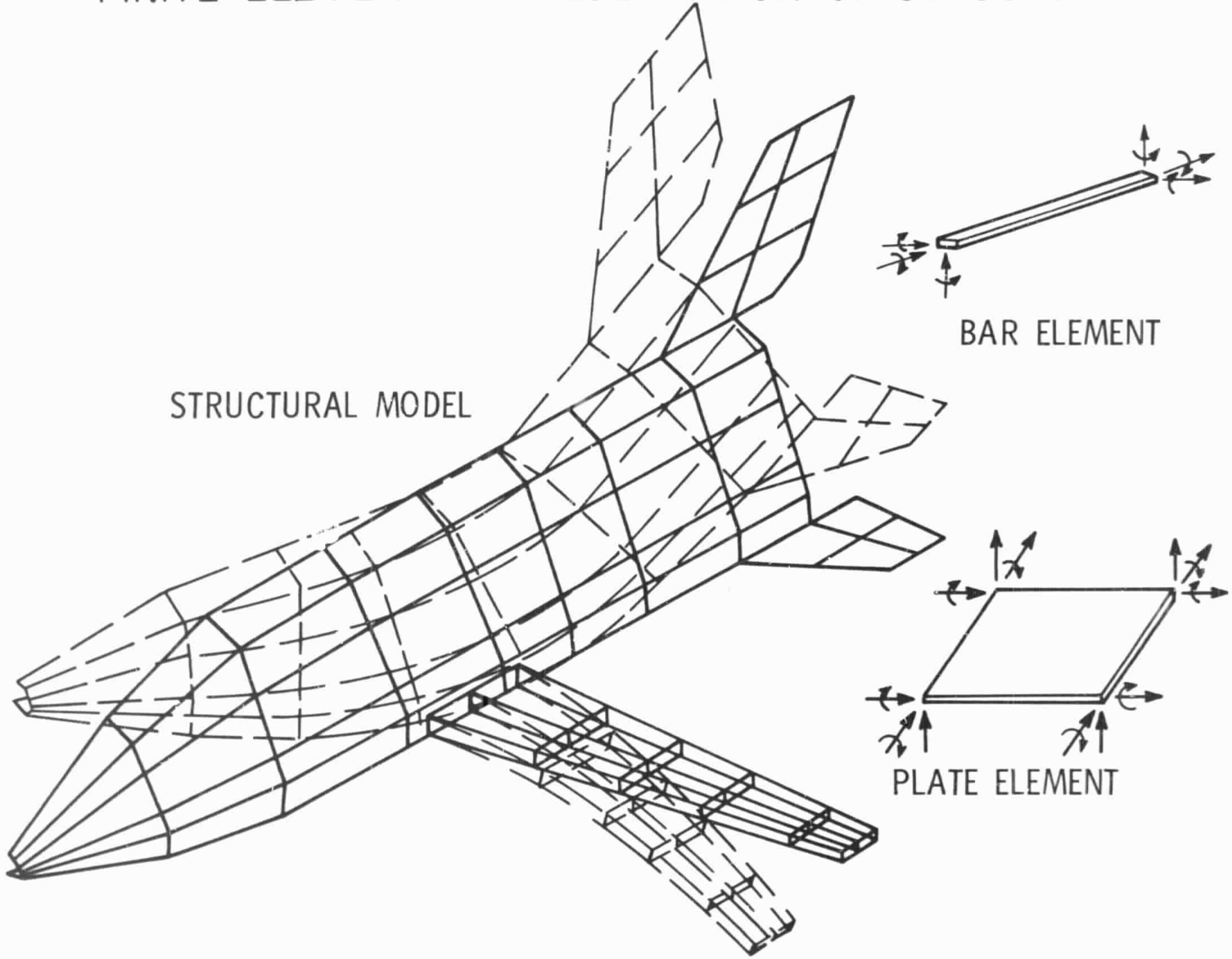
(Slide 16)

Extensive work has been done in many countries over the past 15 years to develop accurate mathematical models for analysis of complex structure. The finite element approach, wherein a structure is represented by an assemblage of bar and plate elements, is currently favored. Computer programs which solve the thousands of simultaneous equations resulting from satisfying continuity and equilibrium conditions between elements are now in existence.

Output from these programs can be displayed graphically, such as the vibration mode shown in the graph, and appropriate modifications to the design can be made with quick visual interpretation of the results of modifications. Because of the many design options in a vehicle as complex as the shuttle, the rapid analysis and redesign capability inherent in modern computerized structural programs becomes a vital technology.

To provide a capability for analysis of complete structures without recourse to programs that are proprietary to many large industrial concerns, and to provide a communication link between industry and government contracting offices, a new structural analysis program is becoming operational in the U. S. Details are provided on the next slide.

FINITE ELEMENT REPRESENTATION OF STRUCTURE



NASA STRUCTURAL ANALYSIS PROGRAM

(Slide 17)

The acronym NASTRAN is drawn from the words NASA Structural Analysis Program. The principal characteristics of NASTRAN are listed on the slide. It provides for the first time a capability for a small group of analysts to investigate entire vehicles in the depth usually reserved for the largest industrial organizations. It has been undergoing operational shakedown for about 1 year in selected government and industrial laboratories and will be released in September of this year through COSMIC to interested users for a nominal fee.

The need for several improvements have become evident during the past year, as detailed on the slide, and some of these will receive priority because of space shuttle needs; namely, aerodynamic loading and heat transfer capability. The other improvements are primarily related to reducing the required computer run time.

In general, NASTRAN permits a user to accomplish with one program a variety of tasks that ordinarily would require several special purpose programs.

NASA STRUCTURAL ANALYSIS PROGRAM
(NASTRAN)

CHARACTERISTICS

- USER ORIENTED
- NON-PROPRIETARY
- OPERATIONAL ON IBM, CDC AND UNIVAC COMPUTERS
- ENTIRE VEHICLE ANALYSIS
  - STATIC STRESS AND DEFLECTION
  - BUCKLING
  - MODES AND FREQUENCIES
  - TRANSIENT AND RANDOM RESPONSE

NEEDED IMPROVEMENTS

- USER AIDES
  - SUBSTRUCTURING
  - AUTOMATIC NODE GENERATION
- AERODYNAMIC LOADING CAPABILITY
  - STEADY
  - UNSTEADY
- HEAT TRANSFER CAPABILITY
- MORE REALISTIC STRUCTURAL MODELING
  - CURVED ELEMENTS
  - HIGHER ORDER ELEMENTS

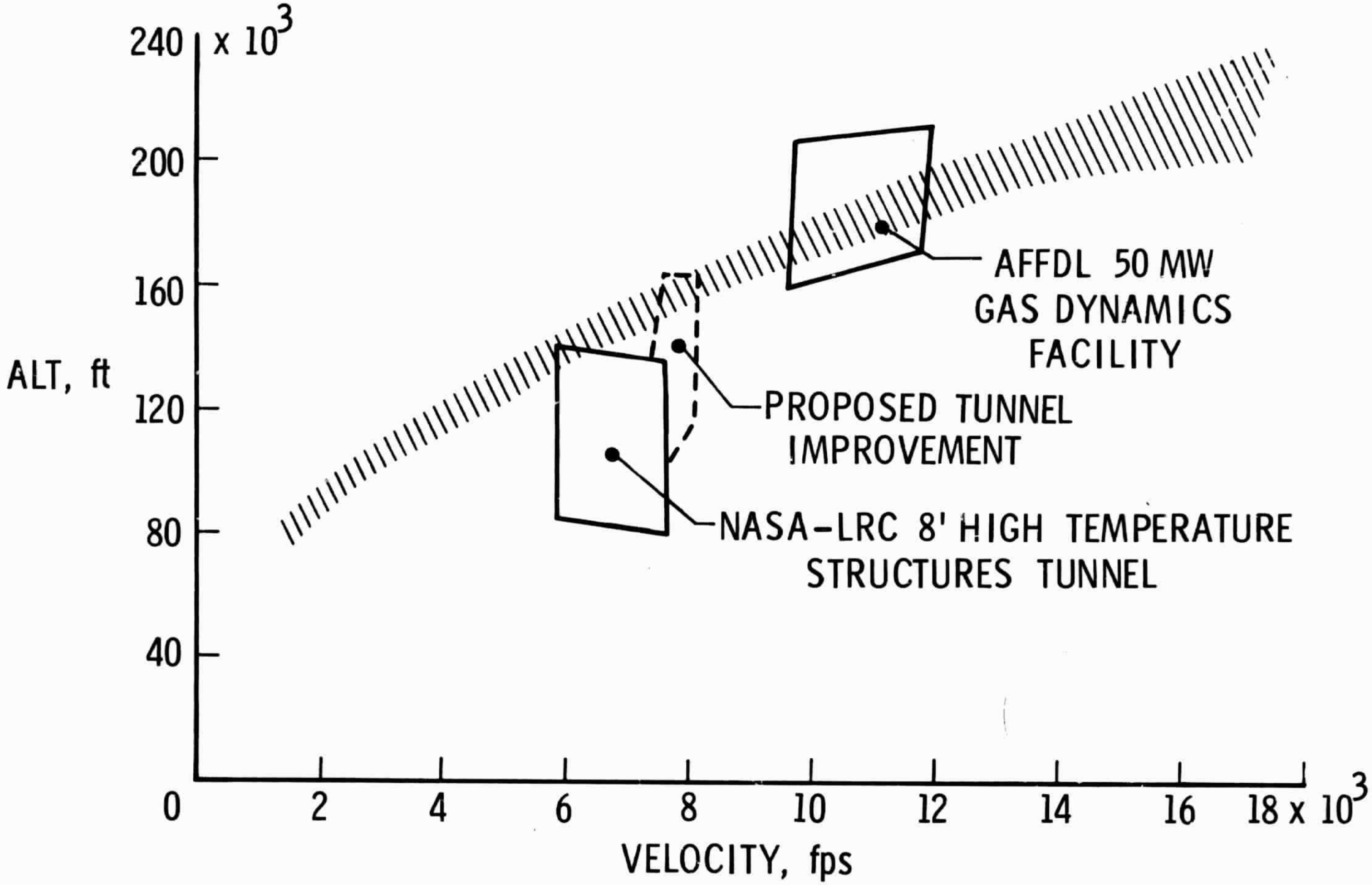
LARGE AERO FACILITIES FOR ORBITER STRUCTURES AND TPS TESTS

(Slide 18)

Facilities for conducting realistic tests of material and structural components under shuttle mission operating environments are in short supply. The problem is relatively more acute in the case of facilities capable of accommodating the larger components in dynamic flow environments as opposed to materials test devices.

Existing aerodynamic facilities which provide true simulation of surface pressure and heating loadings on large scale test specimens are shown on this graph, along with the expected flight trajectory for a reentering orbiter. Simulation is available only at velocities well below those for which maximum heating occurs on the orbiter and then only for tunnel run times substantially less than the duration of significant heating. However, important checks upon the aeroelastic response of heat shields can be made as well as upon heat transfer effects such as those due to full scale proturbances, gaps, and shock interactions. The types and sizes of test specimens that can be accommodated by these structural test facilities are indicated by the next 2 slides.

LARGE AERO FACILITIES FOR ORBITER STRUCTURES AND TPS TESTS



THERMAL PROTECTION SYSTEM TEST BED

(Slide 19)

This slide shows a model designed to be used with the AFFDL 50 MW Gas Dynamics Facility. It is about 2 meters long and can accommodate various TPS stagnation area concepts as well as surface heat shields.

Metallic heat shield panels are shown in place on the lower surface. Detailed measurements can be taken on temperature and mechanical response under the influence of a Mach 12–14 flow field. Tests of this nature are expected to begin this fall on panels of light weight design.


THERMAL PROTECTION SYSTEM TEST BED

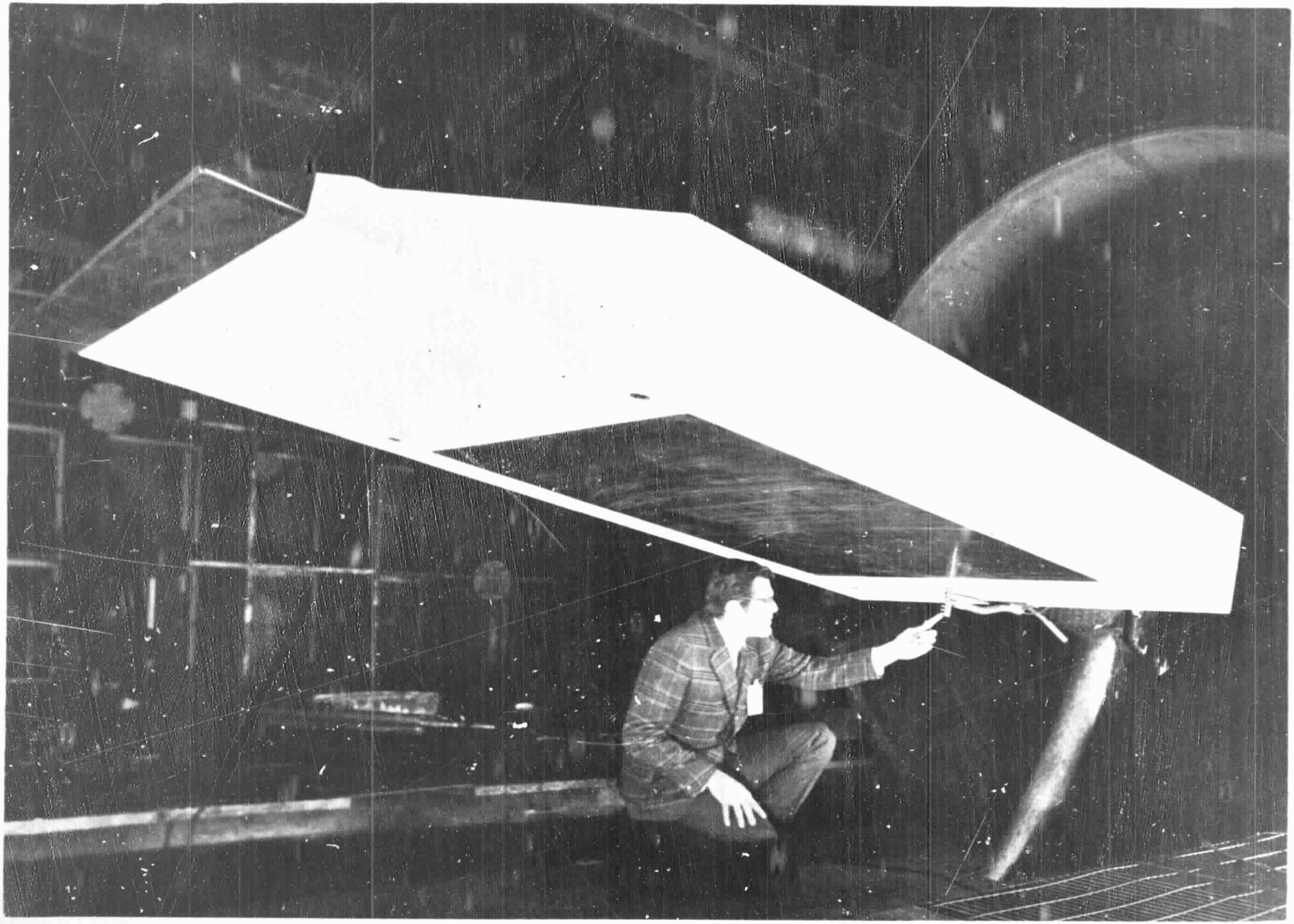
PANEL HOLDER FOR THE 8-FT. HTST

(Slide 20)

A holder for aeroelastic testing of full scale heat shield panels in a two-dimensional flow field is shown. The pressure difference across the panel can be regulated through control of the pressure in a cavity behind the panel.

In the Mach 7 high temperature environment provided by the 8-ft. HTST, any degradation in panel stiffness caused by in-plane thermal stresses will show up as warpage or possibly panel flutter.

NASA
L-70-517

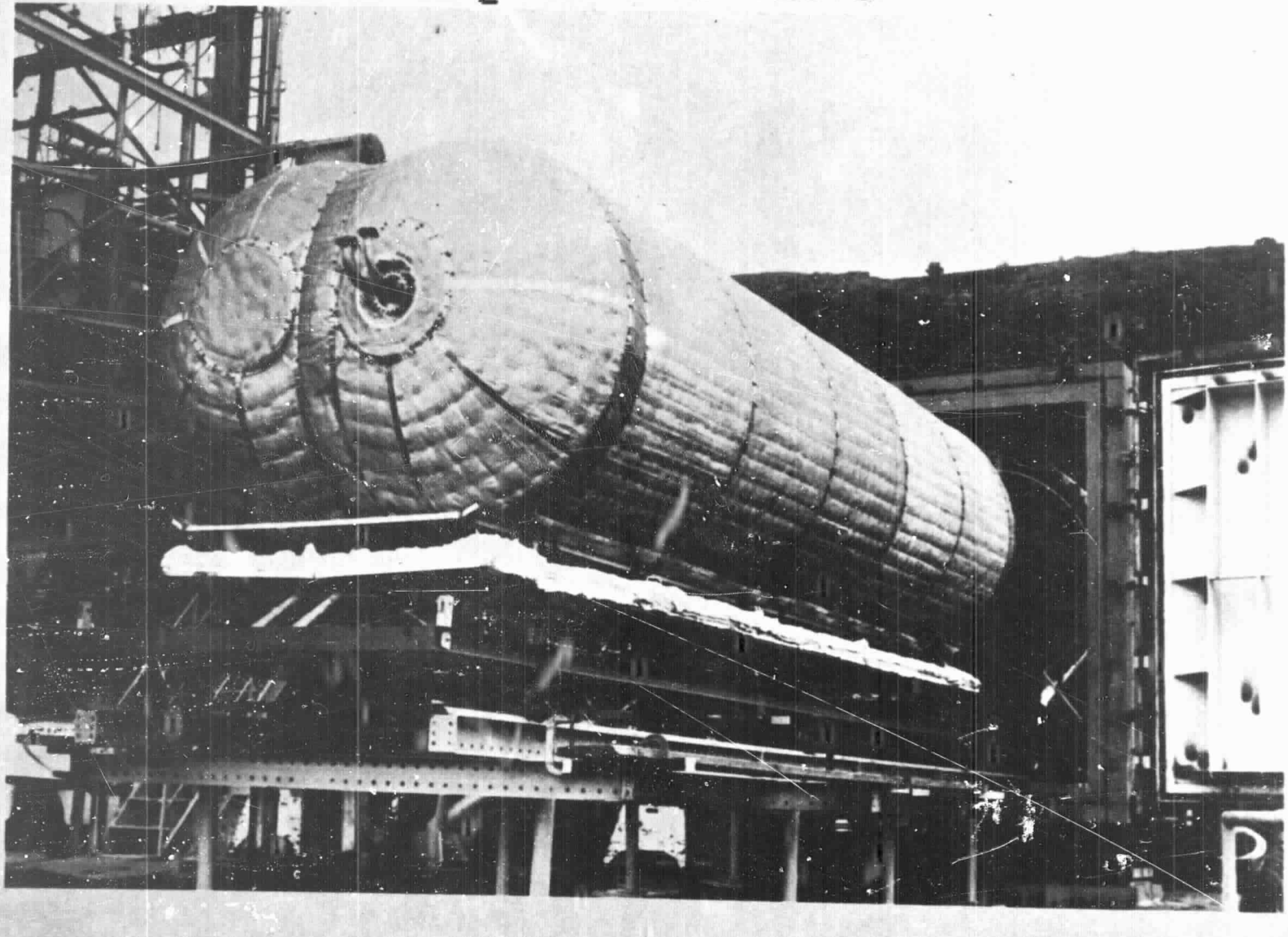


TESTS OF INSULATED CRYOGENIC TANKAGE

(Slide 21)

A number of tests have been run in the past few years with the objective of developing light weight insulation systems capable of inhibiting condensation and freezing of atmospheric constituents on cryogenic propellant tankage. The test depicted in the slide was carried out in industry under government contract. It involved large LH_2 tankage and external insulation and an inert gas purge system to control condensate formation in the insulation layer. The system was subjected to simulated LH_2 fill, ground hold, and ascent heating cycles with control of ambient pressures during each phase of the cycle.

LH_2 TANKAGE TESTS

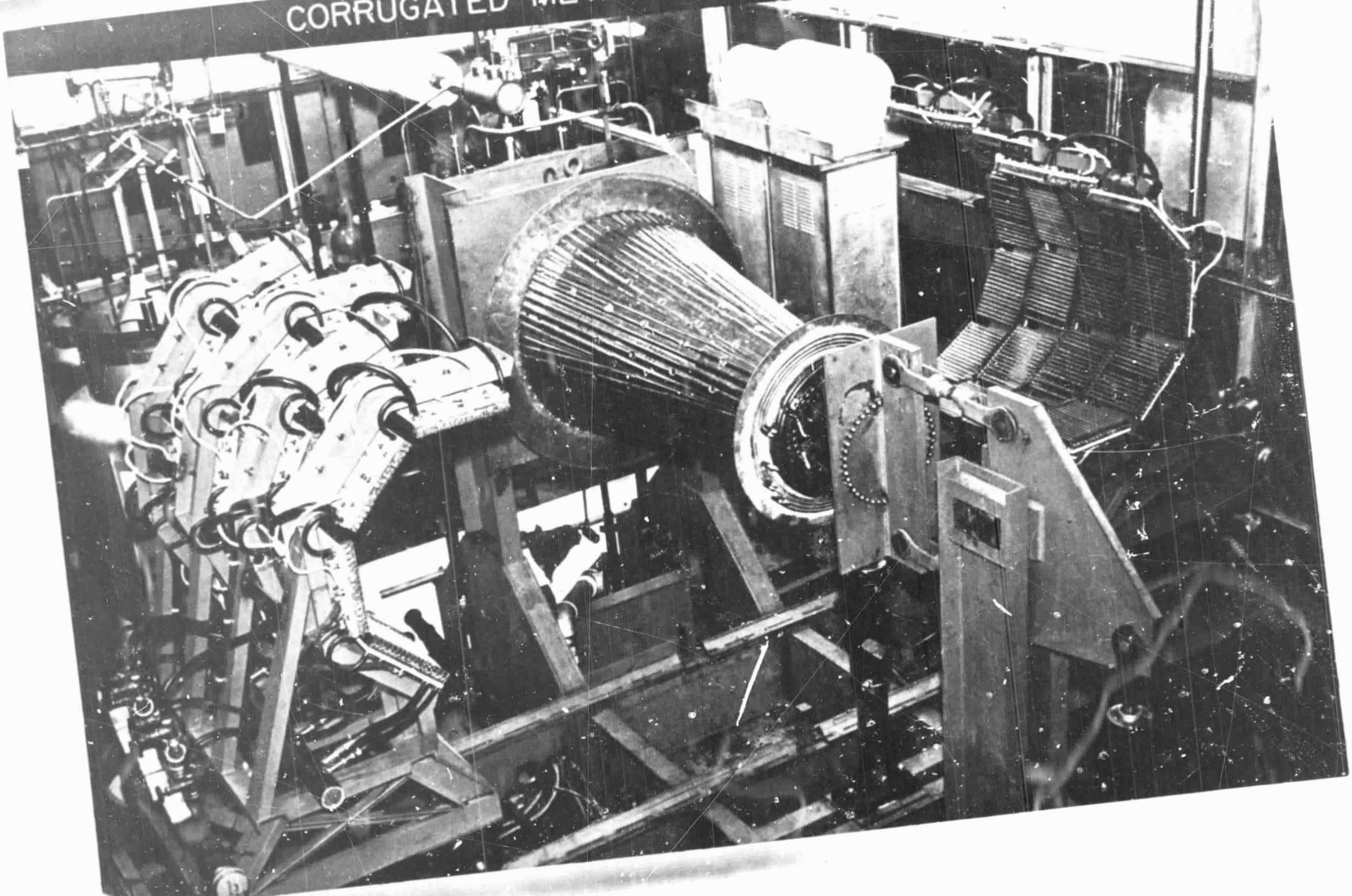


CORRUGATED METAL HEAT SHIELD TESTS

(Slide 22)

A conical test structure about 2 meters long containing insulated cryogenic tanks, high temperature insulation and metallic heat shields has been subjected to radiant heating tests in the laboratory. The objective was to determine thermal strain compatibility of the multi-layered structure and to measure temperature-time histories during simulated mission cycles. A CO_2 gas purge system was also investigated to determine insulation performance with light quantities of CO_2 frost deposition in the insulation layers. This experimental data is now being analyzed and compared with theoretical predictions.

CORRUGATED METAL HEAT SHIELD TESTS



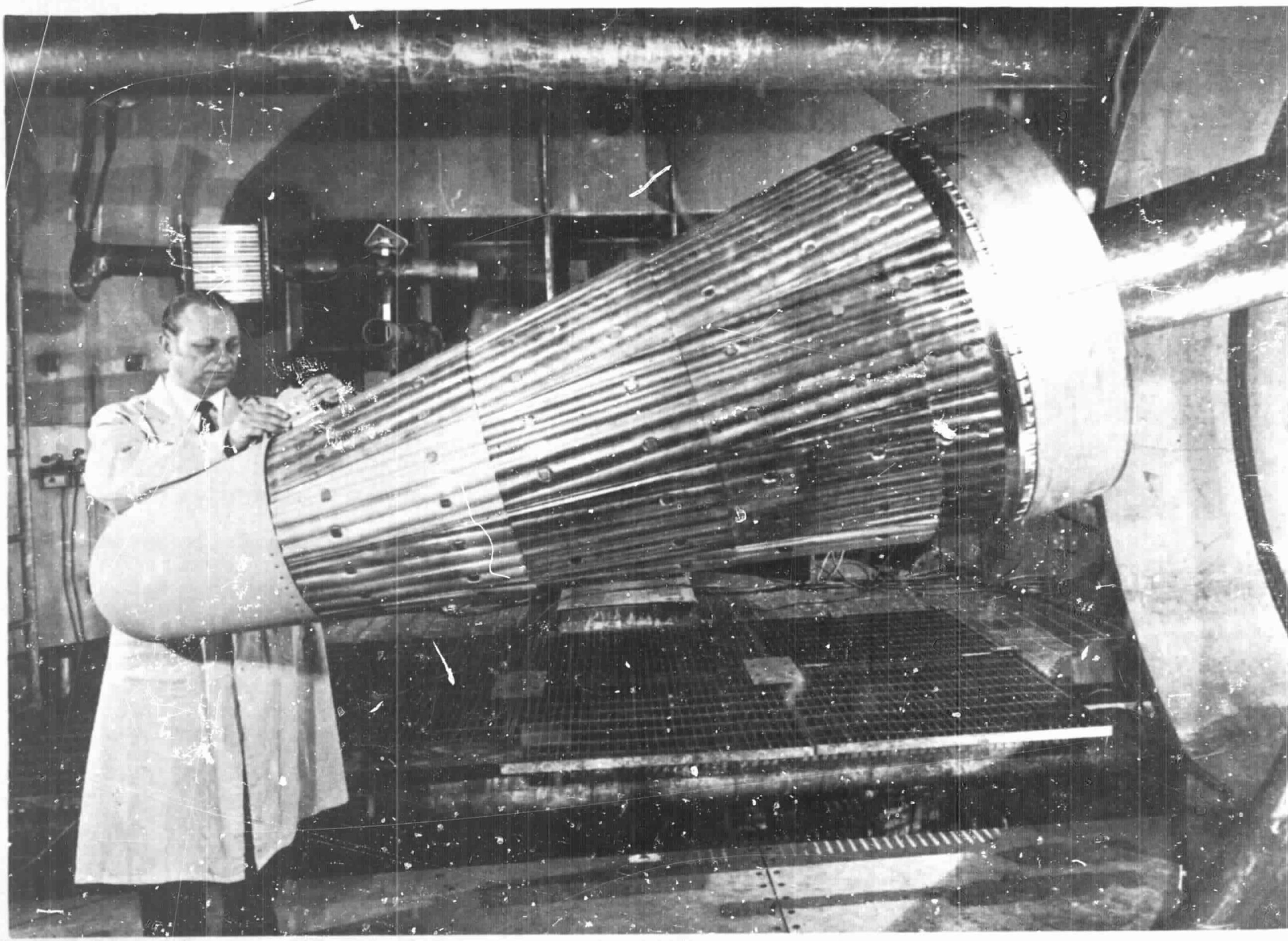
WIND TUNNEL TEST OF THERMALLY PROTECTED STRUCTURE

(Slide 23)

The static test model shown in the previous slide has now been fitted with a coated tantalum nose for testing in the 8-foot high temperature structures tunnel environment. Initial tests resulted in heat shield failures caused by abrupt pressure changes associated with start-up procedures in the tunnel. Tunnel operating procedures are currently being modified to produce gradual ambient pressure changes during start-up and shutdown.

It is anticipated that light weight thermally shielded structures of the size shown can be successfully proof tested in a realistic flight environment before committment to flight tests on the shuttle vehicle.

NASA
L-70-877



TECHNOLOGY – STRUCTURES AND THERMAL PROTECTION SYSTEMS

By

Roger A. Anderson
NASA Langley Research Center
Hampton, Virginia

SUMMARY

The principal uncertainties currently of concern to the structural designer as he views the space shuttle have been identified. Those uncertainties which are specific to the mission but relatively independent of aerodynamic configurations are amenable to attack in a technology development program.

Some of the highlights of this on-going program have been described. The program is focused on those technical areas where design data and hence confidence is deficient and where a significant potential for saving structural weight is evident. The program is designed to produce results in the time scale currently anticipated for development of the shuttle.

As indicated in the text, there are numerous problem areas for which more definitive data or better design solutions are still being sought. No pretext is made that all potential problems have been identified; it is anticipated, however, that as mission simulation testing proceeds these unforeseen problem areas will be exposed.